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PRELIMINARY DESIGN OF A MODEL TO ASSESS THE EFFECT OF SPACE SURVEILLANCE NETWORK (SSN) SENSOR UPGRADES ON ORBIT PREDICTION ACCURACIES RELATIVE TO THE U.S. ANTI-SATELLITE (ASAT) MISSION

THESIS

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Space Operations

Daniel L. O'Brien, B.A.

Captain, USAF

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Daniel L. O'Brien

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Abstract

This study gives a basis for implementation of a model to assess the effect of proposed sensor upgrades to the Space Surveillance Network (SSN) to determine if more accurate orbital element set predictions by the Space Surveillance Center (SSC) can be obtained for U.S. anti-satellite (ASAT) targeting. Because the study is limited to the ASAT mission of the SSC, handoff orbital element set predictions to nearby ASAT facilities for single, low-orbit satellite passes over a single radar sensor are considered. Model development began with simulation of the selected satellites passing over the selected sensors producing baseline truth observations based on the NORAD Simplified General Perturbations (SGP4) model. Sensor errors, in the form of biases and standard deviations were then factored into the model to produce representative sensor observations from the baseline truth observations. A detailed statistical analysis was performed, utilizing experimental design techniques, to allow for follow-on model development to input the representative observations into a differential correction process to produce predicted orbits. Statistical techniques were addressed to enable comparison of alternative proposed upgrades to the SSN. The preliminary model is designed to closely imitate the real-world of ephemeris computation with consideration of perturbation and differential correction processes.

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I. Introduction

Background

With the launch of SPUTNIK I on 4 October 1957, the United States realized the need for a capability to detect, track, and identify man-made objects in space (7:11-10). In response to this realization, an intensive effort began, that continues today, to create and maintain a system of sensors to keep track of artificial satellites (7:12-10). Under the auspices of the United States Space Command's (USSPACECOM) national defense mission, the Space Surveillance Center (SSC), has the mission to detect, track, identify, and maintain surveillance on all man-made objects in earth orbit through tasking requirements levied on the Space Surveillance Network (SSN) (6:1-11).

The mission of the SSN is to provide the SSC with surveillance data on all earth-orbiting satellites and to detect newly launched foreign satellites. The sensor sites of the SSN transmit space surveillance (metric) and space object identification (SOI) data to Cheyenne Mountain AFB

(CMAFB). Within CMAFB, the data is routed to the Space Surveillance Center or the Alternate Space Surveillance Center (ASSC) at NAVSPASUR in Dahlgren, VA (11:2-1).

The SSC uses this data to classify and identify all detected objects, maintain an accurate and current catalog of space objects, and provide orbital data on space objects to military, civilian, and scientific agencies (7:12-10). Orbital element sets, provided to the above agencies, are used for many applications including: detection and tracking of new space launches, identification of foreign satellite functions, information for collision avoidance, satellite decay and impact predictions, warning of attack on U.S. space assets, and targeting information for the U.S. anti-satellite (ASAT) system (7:12-10 to 7:12-11). An orbital element set is a set of parameters which uniquely defines an orbit (6:2-5). The accuracy of the orbital element sets generated by the SSC is a key factor in accomplishment of the above applications.

Research Objective

The objective of this research is to prepare a preliminary design of a model to assess the effect of proposed sensor upgrades to the SSN to determine if more accurate orbital element set predictions can be obtained for ASAT targeting.

Improvement in the accuracy of these orbital element sets may be beneficial. A possible means of improvement is through upgrade of the various sensors or of the computational capabilities of the SSC. Every year, the Air Force has to evaluate potential upgrades, or Engineering Change Proposals (ECPs), to one or more sensors of the SSN. But the Air Force does not currently have the capability to determine how the ECPs contribute to ephemeris accuracy generated at the SSC. This research will focus on assessing the improvement of sensor accuracies rather than computational capabilities of the SSC (1:1).

The measure of performance to assess the effect of sensor upgrades is defined as the probability of ASAT engagement. It will be measured by comparing required accuracies (in terms of three components to be later defined in the study) of the ASAT weapon with the orbit prediction accuracies.

Scope and Limitations

This research is limited to one aspect of the SSC's mission -- targeting information for the U.S. ASAT system -- yet, findings could be generalized for a broader range of SSC orbital element set applications.

The term ASAT generally refers to both anti-ASAT and anti-satellite operations. Initial U.S. ASAT systems are not required to meet an anti-ASAT requirement (31:2). With a focus on near-term ASAT systems, this research will use the term ASAT to specifically refer only to anti-satellite operations.

Because this study is limited to the ASAT mission of the SSC, only orbital element set predictions for low-orbit satellites will be addressed. By limiting the scope to low-orbiting satellites, only radar sensors of the SSN will be included in the study. The optical sensors of the SSN are primarily tasked with deep-space surveillance.

The model will only address single satellite passes over a single sensor. This is consistent with an ASAT scenario in which a single sensor would generate observations for a handoff prediction to an ASAT facility (12:3-25). Preliminary orbit determination from several sensors is assumed to have been made at the time the single sensor begins tracking for the handoff. Given the short time requirements in an ASAT scenario, it is likely that only a single sensor will be available for the final handoff prediction. Also, if the satellite maneuvers after the last orbit prediction was made and before passing over the single sensor for handoff, the single sensor orbit determination is needed to correct for small in-plane maneuvers or possibly abort the mission if a large out-of-plane maneuver is detected (15:4-16).

Overview

Chapter Two provides a literature review of the SSN, sensor and orbit prediction accuracies, and the SSC's orbital element set computation methods. Chapter Three describes the methodology used for development of the preliminary and follow-on models. Chapter Four presents an analysis of the models. And lastly, Chapter Five draws conclusions of the study and suggests recommendations for further study.

II. Literature Review

Introduction

The following paragraphs will review literature pertinent to this research. The specific topics discussed are the Space Surveillance Network, measurement accuracies, the Space Surveillance Center's orbital element computation methods, and previous analyses.

Space Surveillance Network

Sensors of the SSN are broken into three categories: dedicated, collateral, and contributing. Dedicated sensors have a primary unclassified mission of SSN support. Collateral sensors have a primary unclassified mission other than SSN support. Contributing sensors are those owned and operated by other agencies but which provide SSN support when they are not performing their primary missions. Figure 1 shows the location and category of sensors that support the SSN (6:3-4).

The SSN uses two types of sensors: radar and optical. Radar sensors measure radiation in the radio region of the electromagnetic spectrum. Among the radar sensors are mechanically tracking (fan and steerable), phased array, and interferometer. Radar fans are large, stationary antennas with mechanically moving feeds (17:585). As collateral sensors, their primary mission is detection of incoming

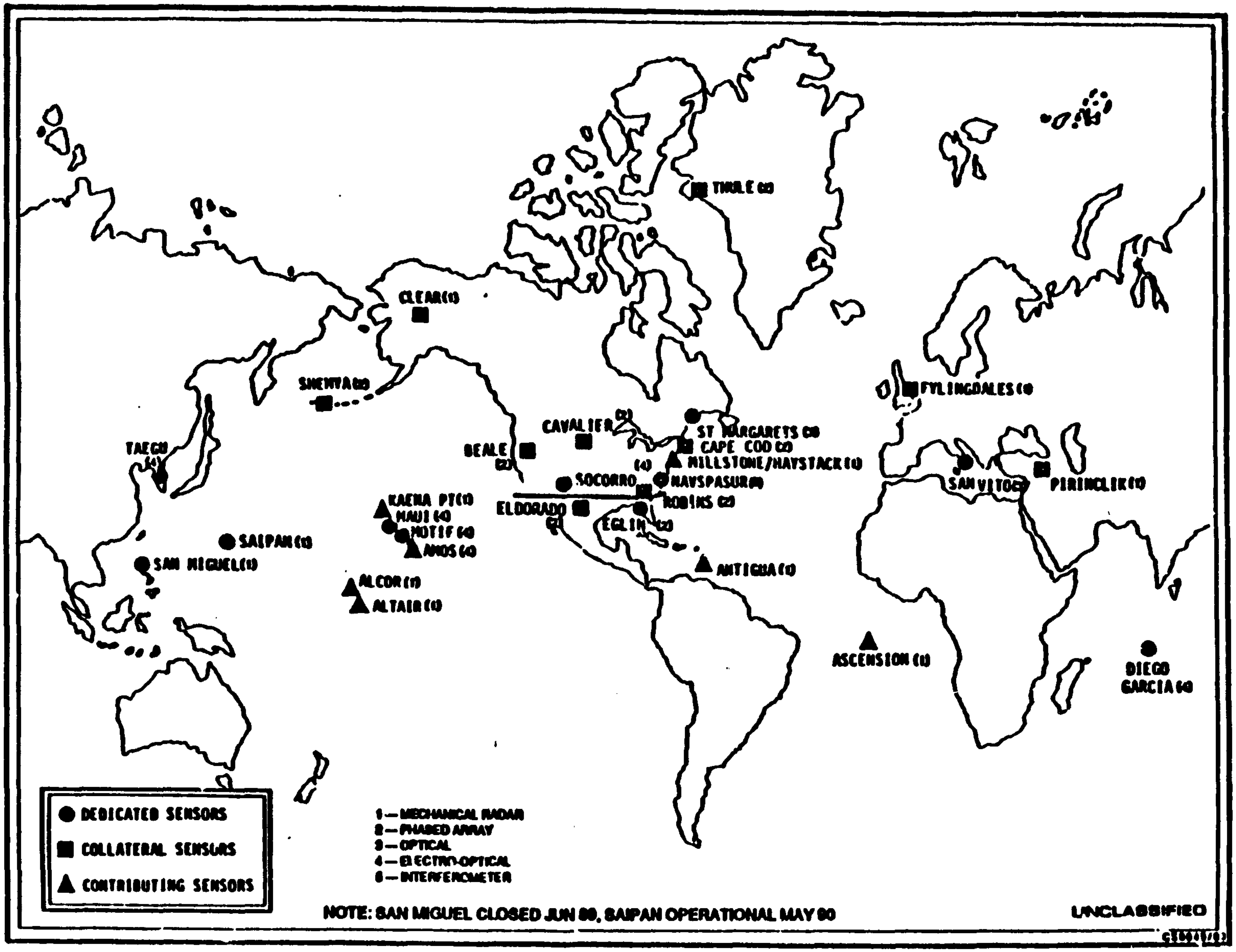

Figure 1. SSN Sensors (Reprinted from 10:2-3)

missiles, but secondarily they track near-earth satellites. Phased array radars use electronically steerable beams that can simultaneously track multiple targets. One dedicated phased array radar at Eglin AFB, Florida, tracks both near-earth and deep-space satellites, while the others are collateral sensors that track near-earth satellites. The one interferometer radar, operated by Navy Space Surveillance (NAVSPASUR) uses three transmitting and six receiving antennas located along an arc from Georgia to California. In effect, it serves as a 5,000-mile-long, 15,000-mile-high radar fence (17:585). Figure 2 shows coverage of radar sensors for satellite altitudes of 185 km.

Optical sensors, on the other hand, measure the radiant energy emitted or reflected by a body. There are three types of optical sensors in the SSN: the Baker-Nunn cameras, the Ground Based Electro-Optical Deep Space Surveillance System (GEODSS), and the Maui Optical Testing Infrared Facility (MOTIF). The optical sensors are the primary source for tracking deep-space satellites.

Measurement Accuracies

Two types of measurement accuracies need to be defined -- individual sensor accuracies and orbit prediction accuracies.

Individual sensor accuracies refer to the accuracy of their observations (position and, for most sensors, velocity). Radar sensor measurements are in terms of azimuth (deg), elevation (deg), range (km), and sometimes

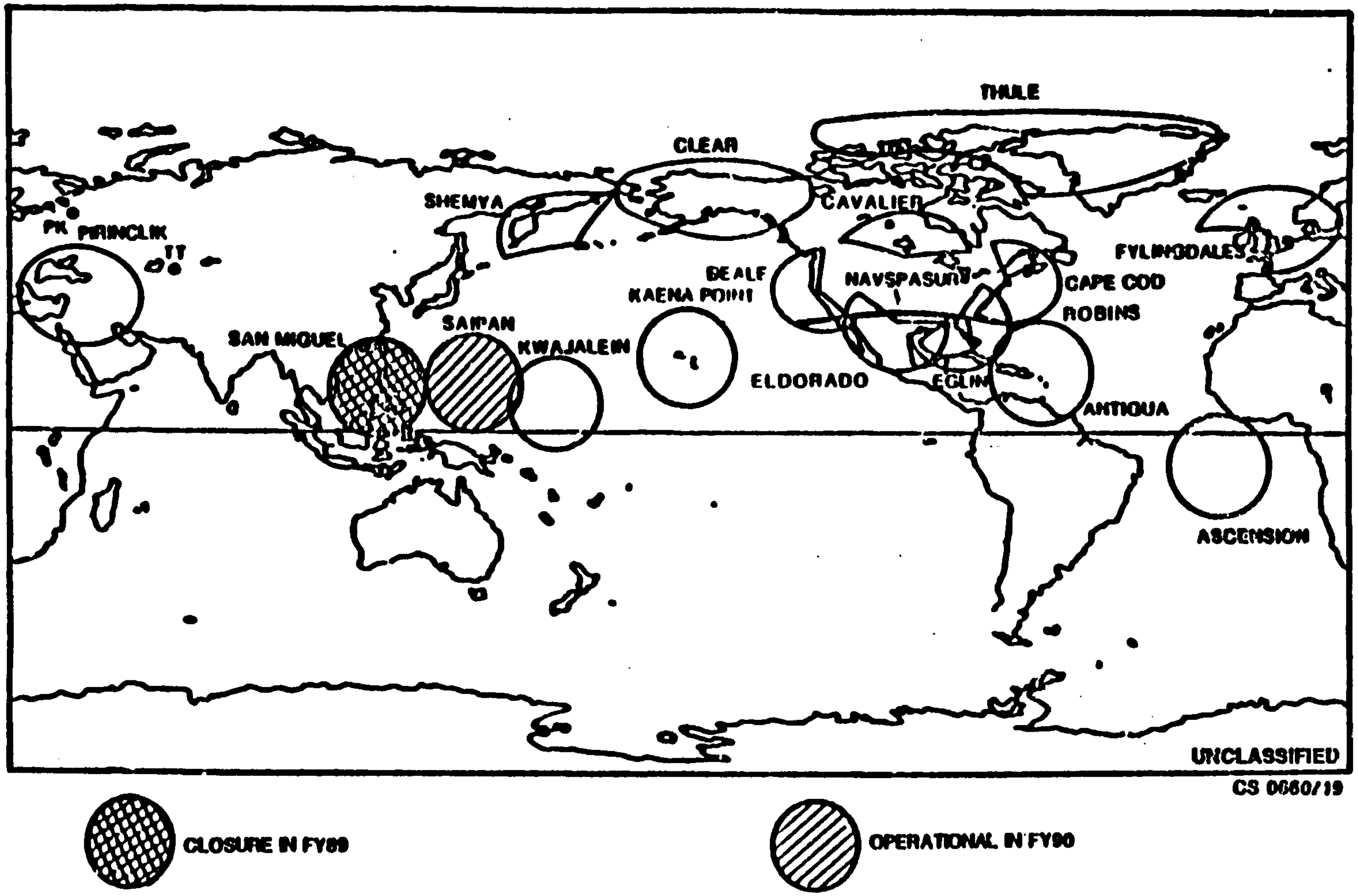

Figure 2. Sensor Coverage (185 km) (Reprinted from 10:2-9)

range-rate (km/sec). Optical sensor measurements are in terms of right ascension (deg) and declination (deg) (12:4-6). Each observation from a sensor has associated with it unique errors -- biases and a standard deviation about the bias. A sample of radar sensor standard deviations and bias errors of the SSN are shown in Tables 1 and 2, respectively. Table 1 shows that the sensor accuracies can vary from .009 degrees to .048 degrees in angles and 3.5 meters to 2.7 km in range (12:4-4 to 4-5). The standard deviation about the bias will be termed the "sigma" throughout the rest of this study.

In general, measurement accuracies are a function of radar characteristics such as pulse length, doppler filter bandwidth, antenna beamwidth, and radar signal processing methods (16:102). Range accuracy is primarily determined by pulse width; range-rate accuracy depends on the frequency separation of two adjacent filters (doppler filter bandwidth); and angular measurements (elevation and azimuth) are a function of the antenna half-power beamwidth. A limiting factor, of all the above accuracies is a function of the signal-to-noise ratio (S/N) (16:102-103).

The above accuracies are sensor dependent and do not include measurement errors like viewing geometry. The viewing geometry will have its largest effect on the elevation and azimuth. Elevation measurement errors are largest at low elevations where the atmosphere refracts the radio wave. Azimuth measurement errors increase with increasing elevation.

Table 1

Representative Sensor Standard Deviations

Sensor Number	Azimuth Sigma (deg)	Elevation Sigma (deg)	Range Sigma (km)	Range Rate Sigma (km/sec)
337 (PIR)	.016	.021	.016	.0033
401	.028	.020	.039	.0036
341 (FYL)	.032	.017	.584	.0015
342	.042	.031	2.718	.0022
343	.044	.020	.906	.0033
346 (SNM)	.014	.009	.018	.0014
349 (CLR)	.048	.046	3.106	.0027
359	.042	.032	.026	.0017
354 (ASC)	.012	.023	.115	.0149
363 (ANT)	.010	.015	.089	.0051
382 (ELD)	.030	.021	.029	.0023
383	.024	.021	.031	.0020
384 (ROB)	.037	.026	.0035	.0028
385	.031	.025	.036	.0026
386 (COD)	.039	.034	.037	.0025
387	.044	.031	.018	.0021
393 (SHY)	.028	.017	.016	.0018
394 (THU)	.044	.037	.042	.0009
396 (CAV)	.009	.010	.045	.0010
399 (EGL)	.019	.023	.021	-
745 (NSS)	.009	.016	.423	-

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(reprinted from 10:3-4)

Table 2

Representative Sensor Bias Errors

Sensor Number	Azimuth Bias (deg)	Elevation Bias (deg)	Range Bias (km)	Range Rate Bias (km/sec)	Time Bias (sec)
337 (PIR)	-.001	.000	-.014	-.0011	-.008
401	-.004	-.004	-.056	-.0004	-.017
341 (FYL)	-.005	.038	.143	.0015	.089
342	-.017	-.030	-1.147	.0031	.100
343	-.019	-.006	-1.025	-.0012	.078
346 (SNM)	.002	-.003	-.010	-.0002	-.003
349 (CLR)	-.017	-.010	.703	.0008	.084
359	.029	.008	.122	-.0001	.002
354 (ASC)	-.002	.013	.018	.0006	-.001
363 (ANT)	.004	-.005	.021	.0001	.000
382 (ELD)	-.008	.016	.024	.0001	.003
3[illegible]	.025	.008	.020	.0004	.009
384 (ROB)	-.002	.022	.003	.0004	.014
385	-.006	.012	.039	.0008	.006
386 (COD)	-.008	-.013	.008	.0002	.007
387	.051	.033	.013	.0001	.005
393 (SHY)	-.014	-.008	.005	-.0002	-.005
394 (THU)	.018	.002	.042	-.0002	-.008
396 (CAV)	-.004	-.015	.016	.0007	-.003
399 (EGL)	-.013	-.016	-.029	-	-.001
745 (NSS)	.002	.005	.018	-	-.015

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(reprinted from 10:3-5)

Of particular interest, in this study, is the phased array radar which has some unique characteristics. A limitation of the phased array radar is the broadening of the beam as it is scanned away from broadside (4:195). This limitation effects the angular measurements (elevation and azimuth) which are dependent on the beamwidth (along with the S/N). The variation of beamwidth with scan angle is inversely proportional to the cosine of the angle off broadside (4:195). Therefore, as the array is scanned off broadside, the angular measurements will worsen.

Individual sensor accuracies, in turn, contribute to the orbit prediction accuracies generated by the SSC. The SSC processes the observational data from one or more sensors to produce a predicted position (at some specified time downrange) of the tracked object. The accuracy of these propagated vectors can range from 1-2 kilometers to 120 or more kilometers (11:3-3). These orbit prediction accuracies are measured by the magnitude of the vector from the predicted position to the observed position called a VMAG (measured in km) (2:5-5). The VMAG -- defined in terms of three components: in-track (orbit's time bias), cross-track (orbit's plane bias), and radial (orbit's height bias) -- is the square root of the sum of squares of the three components.

An error in any one or combination of these three components results in actual displacement of the satellite from its true position. For example, the cross-track error can be thought of as the magnitude of the vector (in km), that connects the two different orbital planes of the observed position and predicted position, perpendicular to the predicted position.

Several other factors, besides individual sensor accuracy affect the accuracy of the orbit prediction. The major variables include: (11:3-13)

1. Tasking level
    a. Tracking contacts per day
    b. Mix of sensor qualities
    c. Variations in tracking geometry
2. Orbital perigee altitude
3. Satellite drag characteristics
4. Prediction time
5. Orbit dynamics algorithm; use of general perturbations or special perturbations
6. Orbit estimation algorithm - batch or sequential batch
7. Number of observations
8. Target maneuver frequency
9. Orbital eccentricity
10. Level of solar activity
11. Dominant perturbations (i.e., atmospheric density for low altitude, lunar/solar for high altitude).

Because of the numerous variables that affect orbit prediction, a single number to represent SSN accuracy is not available and wouldn't be very meaningful (12:A2).

Space Surveillance Center Computation Methods

The main computational task of the SSC is the accurate updating of orbital element sets. Orbital element sets change continuously and, without updates, the SSN would lose its capability to identify and track satellites. The various sensors of the SSN send positional metric data or observations to the SSC on satellites as they pass through the sensor's coverage. Observation types are based on how much positional data (which, depends on the type of sensor) is provided on the satellite. Table 3 below shows the classes of observation types received at the SSC. The observation types of the radar sensors used in this study are all Type 3 with the exception of the observations from the Eglin radar which are Type 2.

Observations coming into the SSC from the sensors never fit the position predicted by orbital element sets exactly and require updating. These deviations are results of sensor error in measuring the position of the satellite and changes to a satellite's orbital elements caused by perturbations not modeled by the SSC.

Perturbations are additional forces not considered in Keplerian motion that cause deviations in the orbit of a satellite from the theoretical two-body motion (30:385).

Table 3

Space Surveillance Network Observation Types

Observation Type	Positional Data
0	Time, range rate
1	Time, azimuth, elevation
2	Time, azimuth, elevation, range
3	Time, azimuth, elevation, range, range rate
4	Time, azimuth, elevation, range, range rate azimuth rate, elevation rate, range acceleration
5	Time, declination, right ascension
6	Time, range
7	Time, EFG vector
8	Time, direction cosines, range
9	Time, direction cosines, range, range rate

(Adapted from 23:211)

The effect of these forces depends on the satellite's size, shape, mass, and orbit. The major perturbative forces acting on satellites are due to the earth's mass asymmetries, atmospheric drag, other mass bodies (such as the sun and moon), radiation pressure from the solar wind, and eletromagnetic drag caused by the earth's magnetic field (6:6-4 to 6-5).

Updating of orbital element sets is done by the mathematical method of differential corrections. Before a differential correction is applied, though, a base orbital element set is computed from the observations sent in by the SSN. This initial computation is done with the assumption of perfect two-body motion (6:6-5).

This initial element set is compared to the predicted satellite position for accuracy to determine if the element set needs to be updated. If the determination is made (depending on the satellite's status and mission) to update the element set, a differential correction is computed (6:6-6).

Differential correction goes beyond perfect two-body motion by incorporating perturbations and sensor errors. Orbital elements obtained from a two-body calculation do not vary with time. However, when perturbation forces are accounted for, orbital element sets will tend to vary with time (8:318). Through differential correction of the base orbital elements, a set of instantaneous orbital elements (ephemeris) can be computed that are as correct as possible at a given instant in time (8:318).

Differential correction is an iterative process that may converge to a best fit ellipse of observations of a particular satellite. Convergence occurs when the difference in orbital elements between two successive iterations becomes smaller than some predetermined tolerance. In order for a differential correction to compute a good description of the ellipse, observations from the SSN must be spread out over as much of the orbit as possible. If observations are taken from tracks of a single sensor, there could be several ellipses that could be fitted to the observation points. Additional observations from displaced sensors quickly narrow the possible ellipse fits (6:6-6 to 6-8).

The SSC uses two types of perturbation models within the differential correction method -- general and special. The general perturbation model (SGP4) uses a fourth-order geopotential model (6:6-9). The four geopotential effects the model accounts for are: the origin's displacement from the earth's center of mass, the earth's oblate shape, the earth's greater mass presence in the southern hemisphere, and other observed mass anomalies. The special perturbations model takes into account more perturbations -- up to a 24th-order geopotential model, a complex atmospheric model (Jacchia - Nicolet model), along with gravitational effects of the sun, moon, and planets. The atmospheric model accounts for diurnal bulge, solar activity, geomagnetic activity, and seasonal variations. The 24th-order geopotential model is not used (6th, 8th, or 12th order is used) because the accuracies are very small when compared to sensor inaccuracies, which effectively reduces the overall accuracy. Because of its complexity, the special perturbation model requires more computer processing time than the general perturbation model (6:6-9 to 6-10 and 6-15).

Previous Analyses

Numerous analyses of orbit prediction accuracies have been done in the past. A recent study by Science Applications International Corp. (SAIC) "Final Report of the Space Surveillance/Command and Control Evaluation Study", provides a survey of 16 studies dating as far back as 1970 done by such companies as Aerospace, Mitre, Boeing, and Xontech (11:3-13 to 3-27). These studies generally fall into three types of analysis: historical data, covariance matrices, and Monte Carlo simulation.

The majority of the studies, including the SAIC study mentioned above, used the historical analysis approach. Studies were based on running limited amounts of historical data through the computational facilities of the SSC; or, in most cases, through "SSC-like" programs. The problem with this type of experimentation is that several runs have to be made to obtain confidence in the responses. The number of historical data sets run for a particular experiment directly relates to the number of runs in a simulation model. In these studies, whether the historical data chosen is truly representative (which is largely based on the number of data sets) is not addressed. A good example can be found in the SAIC study mentioned. One portion of the study ranked the accuracy of the different sensors of the SSN pertaining to single sensor/handoff orbit predictions. This ranking was based on historical data, that, in some cases, was based on one sample. Three of the sensors ranked only had one sample of data from a satellite pass and the most samples used for a sensor was 24.

A major study done by the Anser Corp. in 1981 utilized covariance analysis. This study was based on the questionable assumption (and the reason it is not used by the Air Force today) that "the distance of a "Keplerian" satellite from a Keplerian-estimated position should approximate the distance of a "real world" satellite from a position estimated via perturbation theory" (28:3).

Only one analysis, developed by the Aerospace Corporation in 1978, was done using Monte Carlo simulation. Monte Carlo simulation refers to the scheme of using random numbers to solve certain stochastic or deterministic problems where the passage of time does not play a substantial role. This analysis was not used by the Air Force, though, because the simulation was too costly and computationally intensive (11:5-2). The state-of-the-art statistical methods for simulation, at the time of the study in 1978, were behind today's state-of-the-art (21:v). Also, today's computers are far more capable of efficiently running large-scale models. Therefore, a Monte Carlo-type simulation (which this study proposes) should be reevaluated in light of today's state-of-the-art methodologies and resources.

III. Methodology

U.S ASAT Scenario

The initial system of the near-term Army ground-based ASAT forces will use direct-ascent, ground-launched missiles to destroy targets and will be supported by the ground-based SSN (31:30). Initial deployment is scheduled for June 1998 with one battery of ASAT weapons within the continental U.S. of 50 to 100 missiles (20:23; 13:1; 14:12).

The proposed design (Rockwell is prime contractor) is a three-staged ASAT missile that will only reach low-orbiting satellites. The launch site will likely either be from an island or a coastal area (20:23). This basing would allow for booster flight over international waters, thereby, avoiding spent boosters crashing on inhabited areas (25:76). The interceptor, equipped with a visible light sensor, would extend a sheet of Mylar (a type of polyester film) which would strike the target and disable it. In this way, the target will simply become inoperative and will not create space debris. The interceptor would then burn up on re-entry (20:23).

With likely basing of the initial system in the continental U.S. (based on the homeland sanctuary), sensors within the U.S. will play a key role (25:76). A scenario based on these considerations could entail a sensor (say, Eldorado) sending a "flash" element set to the ASAT facility (say, located on the east coast of the U.S. or colocated with the ASAT facility) for a short (less than 10 minutes) handoff orbit prediction (10:1-6). This is based on the assumption that the ASAT facility will be able to process observational data if the sensor does not have the capability. If the sensor were to be located on the west coast of the U.S. handoff predictions could come from the Pacific sites (possibly Altair at Kwajelein) for orbit predictions at about a quarter revolution of the satellite's (about 20 minutes) orbit.

If the basing does not end up being within the U.S., a likely site would be Kwajelein. Since Kwajelein is located near the equator, it has the unique capability of being able to directly launch an ASAT weapon into any orbital inclination.

Accuracy requirements for the proposed weapon are assumed to be in the same terms as an earlier ASAT weapon design -- the F-15 Air Launched ASAT (ALASAT). The required accuracy for the ground-based ASAT weapon will therefore be defined in terms of maximum cross-track, in-track, and radial distance errors. Information on the size of these accuracies are classified. Even though the proposed ASAT weapon is uniquely different than the ALASAT, the above assumption is reasonable. Accuracy requirements have a large dependence on the closing speed of the weapon relative to the target. Faster closing speeds will require higher accuracies since the weapon will not have as much time to make adjustments.

The ALASAT would have very high closing speeds (terminal velocity of about 13 km) compared to the proposed ASAT. The proposed ASAT will almost have to "stop" next to the target in order to swat at it. Therefore, in this regard, the proposed system may have less stringent accuracy requirements.

The "USSPACECOM Anti-Satellite (ASAT) Concept of Operations (CONOPS)" provides the framework for background for employment of ASAT weapons. This CONOPS addresses the operational concept for the battle management/command, control, and communications; employment; and support of all ASAT systems under USCINCSPACE (31:1). This research will focus on the employment, in particular -- the execution phase, of the CONOPS.

The execution phase includes actions necessary to implement engagement plans as well as post-attack assessments (31:27). The engagement plans, developed at the component level (the SSC), evolve from general guidelines initiated at the National Command Authority (NCA) level. These guidelines will generally include: a description of the situation; the mission, objectives, and assumptions; and timing requirements (31:22). The engagement plan contains a dynamically-updated annex which includes: the satellites to be targeted; the ASAT facility that will engage with engagement timing; and SSN tracking requirements (sites, times) for pre and post attack.

This research will address the ASAT scenario from the point of execution where the engagement plan has been formulated. Numerous conclusive studies have been done on sensor coverage and windows of engagement and the Air Force now has a high interest in the accuracy aspects of sensor improvements (1). Therefore, the success rate (probability of ASAT engagement) of the execution phase will be studied relative to sensor accuracies.

Sensor Selection and Description

Selection of sensors for this research was limited to near-earth sensors. Deep-space sensors were eliminated since any near-term ASAT targeting scenario would not include deep-space satellites. Of the 16 near-earth sensors, five were chosen for use in this study. Table 4 shows these five sensors, along with the important sensor characteristics needed for this study.

Observations from Eglin, Cavalier, Shemya, and PAVE PAWS represent a large portion of the near-earth observations, accounting for over 80 percent of the observations sent to the SSC (24:26). An emphasis is placed on phased array radars, because the mechanical radars, as they age, may become logistically unsupportable in a stricter budget environment. Also, because of a continuing trend of closing forward deployed bases, phased array radars located within the U.S. were considered most important.

Only one radar, Otis, of the four PAVE PAWS radars (others are Beale, Robins, and Eldorado) was chosen under the

TABLE 4

SENSOR CHARACTERISTICS

RADAR	OTIS (PAVE PAWS NE)	SHEMYA (COBRA DANE)	CAVALIER (PARCS)	EGLIN
SENSOR NUMBER	386	393	396	399
SENSOR TYPE	Phased Array	Phased Array	Phased Array	Phased Array
LOCATION				
NLAT (DEG)	41.752	52.737	48.725	30.572
WLONG (DEG)	70.538	185.909	97.900	86.215
MAXIMUM OBS/MIN	100	120	40	120
FREQUENCY OF OBS (SEC)	1	1	2	1
AZIMUTH LIMITS (DEG)	347 to 227	259 to 19	313 to 63	120 to 240
ELEVATION LIMITS (DEG)	3 to 85	3 to 85	1.9 to 105	1.9 to 105

(Compiled from 6:3-20; 29:25,41,45,55,156-157)

assumption that the PAVE PAWS radars would perform similarly given they have like characteristics.

Contributing sensors were not considered because in an ASAT scenario these non-USSPACECOM-owned sensors may not be available.

Despite the large amount of data the selected sensors provide, sensors that provide relatively small amounts of data may be more critical in selected ASAT scenarios because of the location of the ASAT facility. For example, if an ASAT facility were to be located in the U.S., the best handoff prediction might be from the radar sensor at Kwajalein Atoll in the Pacific Ocean. Therefore, because of many possible locations for an ASAT facility, the model could be made to accept different sensors than chosen above to facilitate proper single sensor coverage.

Satellite Selection and Description

Table 5 lists major low-orbiting Soviet satellites (in orbit as of October 1991) that are used as ASAT targets in this study. Through review of The Soviet Year in Space 1990, one satellite was chosen from each low-orbiting Soviet satellite mission area that may be of high interest in an ASAT scenario. Certain high-interest satellites (Radar Ocean Reconnaissance and Photographic Reconnaissance) were not included since there were not any known satellites of this mission type in orbit at the time of the study.

Model Development

Step 1. Simulate satellite passes with the above selected sensors and satellites and produce baseline truth observations in terms of azimuth (Az), elevation (El), range (R), and range-rate (RR).

Truth observations will be produced by a program which generates an ephemeris given the satellite two-line element set, the sensor position (latitude, longitude, and height

TABLE 5

SELECTED SATELLITE POPULATION

MISSION	PAYLOAD NAME	SATELLITE NUMBER	APOGEE/ PERIGEE	REMARKS
Communications	Kosmos 2112	21014	813/ 770 km	1 of a 3-satellite constellation (with Kosmos 1954 and 2056)
Navigation	Kosmos 2100	20804	1014/ 961 km	1 of a 6-satellite constellation (with Kosmos 2004, 2026, 2034, 2061 and 2074)
Remote Sensing	Okean 2	20510	666/ 639 km	
Electronic Intelligence (ELINT)	Kosmos 2058	20465	665/ 634 km	1 of a 6-satellite constellation (with Kosmos 1842, 1908, 1933, 1953 and 1975)
ELINT Ocean Reconnaissance (EORSAT)	Kosmos 2107	20985	417/ 403 km	1 of a 5-satellite constellation (with Kosmos 2046, 2060, 2096 and 2103)
Space Station	Mir	16609	˜375 km	

(Compiled from 18:37-40, 53, 66-68, 85-92,129-133)

above mean sea level), and the time interval of interest. The program will generate these baseline truth observations with the NORAD Simplified General Perturbations (SGP4) model used by the SSC. For low-orbit, single-sensor orbit predictions, the SGP4 model is as accurate as the more complex SP model, therefore SP modeling does not need to be considered (12:3-53).

Data will be generated for each sensor/satellite pass combination possible. Most sensor/satellite combinations generate several passes for any 24-hour period. Passes of varying culminations (different sensor/satellite geometries) will be considered to categorize the range of conditions.

The frequency of observation rates is at the maximum observation rate shown in Table 3. The SSC assigns suffixes (A, B, D, H, M, S, or T) to satellites to determine the amount of observational data required (6:3-11). Suffix "A" requires maximum data on all available passes. In this study, it is assumed in an ASAT scenario that target satellites would have this "A" suffix, thereby, the frequency of observations will be at the maximum possible for each sensor.

The output of the program will give baseline truth observations in terms of the date, time, azimuth, elevation, range, and range-rate for all sensor/satellite combinations across the range of conditions. The convention for naming the output files of these baseline truth observations is SSSOOOOO.TRU. Where, SSS is the sensor number and OOOOO is the satellite number. These single tracks are then used for input to Step 2 below.

Step 2. Add in sensor sigmas and biases to produce representative sensor observations from the baseline truth observations from Step 1.

The sensor sigmas for the five chosen sensors are extracted from Table 1 and the biases are from Table 2. Sensor sigmas and biases vary slightly over time, therefore, an exact value at a certain time can only be determined through calibration at that time. Tables 1 and 2 depict the sensor sigmas and biases for the period from 7-15 November 1988 as measured by the *1988 AFSPACECOM/DOA Metric Accuracy Study*. These values will be used for this study assuming sampling from a normal distribution with mean equal to the bias of the sensor and standard deviation about the bias equal to sigma of the sensor.

A SLAM II/FORTRAN program (see Appendix A) accepts the output from Step 1 (baseline truth observations -- SSSOOOOO.TRU files) and incorporates the sensors' biases and sigmas to produce representative observations for each sensor/satellite combination.

The convention for naming the output files of these representative observations is SSSOOOOO.OUT. Where, SSS is the sensor number and OOOOO is the satellite number. These observations can then used for input to Step 3 below for follow-on model development.

Step 3. Input the representative sensor observations (the SSSOOOOO.out files from Step 2) into a differential correction process to produce predicted orbits at specified time intervals downrange for the handoff to a nearby ASAT facility. These time intervals should be consistent with the ASAT scenario where strict time requirements will apply. The handoff prediction from a single sensor will likely be set up to go to a nearby ASAT facility that can view the satellite within its first revolution after passing the sensor. Orbit predictions will, therefore, need to cover the entire range of the satellite's first revolution past the sensor to account for "flash" element set and complete-revolution handoffs. The orbital period of most low-earth Soviet satellites is between 90 and 105 minutes, as are the periods of the satellites selected for this study. Therefore, to cover the complete range, predicted orbits at 5, 25, 45, 65, 85, and 105 minutes would be reasonable for a simulation.

Steps 1 through 3 will be run through the simulation model a predetermined number of times to produce more precise representation of the responses. Because the model contains stochastic processes, a Monte-Carlo-type simulation will be run where several replications of the stochastic process (generating random observations) have to be made to obtain an expected value with a certain confidence interval (e.g., precision) of the response. Determining this number of runs, along with related considerations will be detailed in the Statistical Analysis section of Chapter IV.

Step 4. Change the sensor sigmas and biases to represent upgraded sensor proposals and repeat Steps 2 and 3. Detailed analysis of this step will follow in Chapter IV.

Step 5. Compare predicted orbits of baseline sensors and upgraded sensors to a NORAD SGP4 baseline truth predicted orbit and analyze the predicted orbits to see if they are statistically different. Detailed analysis of this step will follow in Chapter IV.

IV. Analysis

One set of truth observations (a single pass of a Soviet EORSAT satellite over the Cavalier radar) is shown in Appendix C as a representative sample of the several satellite/sensor combinations and their associated observations considered and calculated in this study. Along with the truth observation (39620985.tru), the observation generated considering the sensor's weights and biases is shown (39620985.out).

Statistical Analysis

Number of Runs. A single simulation run represents one sample of a stochastic process and the random elements of the model will produce outputs that are probabilistic. Therefore, more precise responses can be obtained by performing more runs. If the simulation was run only one time, results could be misleading (26:725).

The observation generation code in Appendix B is based on random sampling from an assumed normal distribution of average sensor sigmas and biases. Since there are not large samples of sensor sigmas and biases readily available, a check of this normal distribution assumption cannot be made empirically. Therefore the assumption is based on the Central Limit Theorem which states, in simplified terms, that, under broad conditions, the distribution of the average or sum of independent observations from any distribution approaches a normal distribution as the number of observations becomes large (26:699). Also, the normal distribution is commonly used for approximating errors of various types (19:335).

A random sample taken from the "tail" of the distribution would produce quite different representative observations than a sample taken at the mean of the distribution. Therefore, predicted observations resulting from a single run of a sampled observation is not truly representative (Appendix C shows a single run of the first stage of the preliminary model). Several runs (replications) have to be made to get an estimate (with a specific confidence interval) of the expected value of the performance measures given random representative observations. In computing this expected value it is assumed that the random variables (the performance measures) from the runs are independent. The independence of the runs is accomplished by using different seed numbers for the sampling portion of the observation generation code each time a run is made (19:532).

Let the performance measures C_j , I_j , R_j be random variables defined on the jth run for $j = 1, 2, \ldots, n$, where n is the number of runs. C_j is the cross-track difference between the observed position and the predicted position; I_j is the in-track difference; and R_j is the radial difference. From this point on, analysis of C_j will follow realizing the same procedure is used for I_j and R_j. To obtain a point estimate and confidence interval for the mean cross-track difference resulting from n runs, one would apply the formula:

$$\bar{C}(n) \pm t_{n-1,1-\frac{\alpha}{2}}\sqrt{\frac{S^2(n)}{n}} \qquad (1)$$

where $\bar{C}(n)$ is the point estimate for μ given by:

$$\bar{C}(n) = \sum_{j=1}^{n} \frac{C_j}{n} \qquad (2)$$

with an approximate 100(1 $-\alpha$) percent ($0 \leq \alpha \leq 1$) confidence interval and the sample variance $S^2(n)$ is given by:

$$S^2(n) = \frac{\sum_{i=1}^{n} [C_i - \bar{C}(n)]^2}{n-1} \qquad (3)$$

The confidence interval based on Equation (1) is called a fixed-sample-size procedure (19:533).

A disadvantage of the fixed-sample-size procedure is that it is based on a predetermined (a guess) number of runs, n. As a result, there is no control over the size of the confidence interval since the interval is dependent on the unknown sample variance. Therefore, a procedure is needed to determine the number of runs required to estimate C with a specified error. There are procedures to find an approximate value of the number of runs required; but, in actuality, the value may turn out to be more runs than needed for the specific error -- resulting in inefficient computer usage (19:538).

A sequential procedure put forth by Law and Kelton obtains the estimate with a specified error that takes only as many runs that are actually needed (19:538). Details of this procedure follow.

The objective of the procedure is to obtain an estimate of C with a relative error of Θ ($0 \le \Theta \le 1$) and a confidence level of $100(1-\alpha)$ percent. The relative error, Θ, is used to specify the confidence interval half-length (e.g., the precision of C). If the estimate C is such that $|\bar{C} - \mu| / |\mu| = \Theta$, then the percentage error in C is 100Θ percent (19:536-537). Choosing an initial number of runs $n_0 >= 2$

$$\beta(n,\alpha) = t_{n-1,1-\frac{\alpha}{2}}\sqrt{\frac{S^2(n)}{n}} \tag{4}$$

is the confidence interval half-length. The sequential procedure is (19-539):

0. Make n_0 runs of the simulation and set $n = n_0$.
1. Compute $\bar{C}(n)$ and $\beta(n,\alpha)$ from $C_1, C_2, \ldots, C_n$.
2. If $\beta(n,\alpha)/|\bar{C}(n)| <= \Theta$, use $\bar{C}(n)$ as the point estimate for μ and stop. Equivalently,

$$[\bar{C}(n) - \beta(n,\alpha) \ , \ \bar{C}(n) + \beta(n,\alpha)] \tag{5}$$

   is an approximate $100(1-\alpha)$ percent confidence interval for μ with the desired error Θ.

3. Otherwise, replace n by (n + 1), make an additional run and go to Step 1.

Law and Kelton recommend starting the sequential procedure with n_0 >= 10 and Θ <= 0.15 (19:539).

The above procedure would also be performed for I_j and R_j. But, with more than one measure of performance (i.e., C_j, I_j, and R_j) the probability that all the measures fall within their confidence interval is not the same as the probability for each measure alone. Actually, the confidence interval for all measures combined follows the Bonferroni Inequality which states the combined confidence interval will have a probability greater than or equal to $[1 - \sum_{s=1}^{k} \alpha_s]$ (19:509). Therefore, if the probability for the confidence intervals for C_j, I_j, and R_j were all 5 percent, the combined probability would be [1 - (.05+.05+.05)] = 85 percent.

Experimental Design. Experimental design in simulation is a statistical technique for improving the efficiency and effectiveness of experiments with the simulated system. It provides a way to decide how to configure the simulation so that the desired output can be obtained with the least amount of runs (19:657; 21:259).

Three basic concepts that need to be understood are: factors, levels, and responses. The factors are the input parameters that are changed during the experiment. The levels are the values given to the factors. And the responses are the values of the output performance measures. A single experiment consists of simulating the orbit predictions obtained from one of the selected satellites passing over one of the selected sensors. Therefore, with six satellites and five sensors, there will be a total of 30 experiments.

Correspondingly, in this study, the factors are the biases and sigma values of the sensors. The levels correspond to whether a sensor is upgraded or not. And the responses are the values of the difference in the cross-track, in-track, and radial components of the satellite's predicted and observed position.

With the number of runs decided through the sequential procedure described earlier, the next step is to decide how to configure the simulation. Namely, which combination of parameter values to actually run.

There are basically three approaches to the design of experiments (21:260):

1. One factor at a time
2. All factor - level combinations: full factorial design (number of levels raised by the number of factors)
3. Specifically selected combinations: incomplete factoral design

In Approach 1, interactions among parameters cannot be analyzed. For example, the azimuth sigma and the elevation sigma could not change simultaneously for a particular run -- only one parameter can change. For this reason, this approach will not be considered in this study.

Approach 2 considers all combinations of factors and levels. If the number of factors is very high, this approach may lead to an impractical (computer intensive) number of combinations.

Approach 3 is used when Approach 2 is impractical and considers a subset of the full factorial design by making assumptions on non-interaction of some parameters.

The intended purpose of this study is to be able to evaluate actual sensor upgrade proposals, as a result, the actual combinations of biases and sigmas will be predetermined by the proposed upgrade. Therefore, Approach 2 can be used considering one factor at two levels.

This makes the running of the model conceptually simple -- just run the model (the number of times determined from the sequential procedure previously discussed) at the two levels of the single factor and form a confidence interval for the expected response of each of the factor levels.

Statistical Significance. In order to use the predicted orbits from the observations of the upgraded sensors as comparisons to the predicted orbit of the truth observations, it must be determined if the difference between the baseline sensor orbit predictions and the upgraded sensor orbit predictions is statistically significant.

A statistical method, termed the Paired-t Confidence Interval, can be used to determine if a system (upgraded sensor's effects on orbit predictions) are statistically significant compared to the standard (the baseline sensors' effect on orbit predictions).

The Paired-t Confidence Interval formulation is as follows (19:587):

Again, first consider one measure of performance C -- the cross-track error. For i=1,2, let C_{i1} , C_{i2} , ... , C_{in_i}, be a sample of n_i observations from System i, and let $\mu_i = E(C_{ij})$ be the expected response. Of interest, is a confidence interval for $\delta = \mu_1 - \mu_2$ -- the difference between the expected value of the upgraded system and the baseline system. If the confidence interval contains zero, reject the hypothesis that the improvements of the upgraded system are statistically significant. If the confidence interval does not contain zero, do not reject the hypothesis. In addition, if the confidence interval does not contain zero, the confidence interval quantifies how much the measures differ.

Pair each C_{1j} with C_{2j} to define $Z_j = C_{1j} - C_{2j}$, for j = 1, 2, ... ,n. Then construct a confidence interval for $E(Z_j) = \delta$:

$$\overline{Z}(n) = \frac{\sum_{j=1}^{n} Z_j}{n} \tag{6}$$

$$\hat{Var}[\overline{Z}(n)] = \frac{\sum_{j=1}^{n} [Z_j - \overline{Z}(n)]^2}{n(n-1)} \tag{7}$$

The approximate $100(1-\alpha)$ percent confidence interval is:

$$\overline{Z}(n) \pm t_{n-1,1-\frac{\alpha}{2}}\sqrt{\hat{var}[\overline{Z}(n)]} \tag{8}$$

With this confidence interval, inferences can be made depending on the presence of zero in the interval.

The model will also allow for comparison between different upgrade proposals. The experiment could be run to determine confidence intervals for the measures of performance -- cross-track, in-track, and radial errors for each upgrade. Each upgrade could then be compared to the baseline to determine if there is a statistical difference as described above. If both cases are determined to be statistically different from the baseline, then the two upgrades can be compared to determine if there is a statistical difference among them. A decision can then be made between the two proposed upgrades based on a comparison of the confidence intervals.

The accuracy requirements of the ASAT weapon must also be considered. One upgrade may provide the required accuracy yet may not be as accurate as an alternative upgrade. Based on the above decision criteria the more accurate upgrade would be chosen. But, cost may be a major consideration and the less accurate upgrade (but one which still meets ASAT requirements) may be chosen.

Another way to approach the cost/benefit analysis is to look at upgrading the ASAT weapon itself. The trade-off, between SSN sensor accuracy improvements and weapon sensor accuracy can be expressed with a simple example. The major parameter in the design of a kinetic-kill ASAT weapon is the field of view (FOV) on the weapon's seeker -- in terms of cross-track, in-track, and radial track components (22). If a certain sensor's performance measures (as defined in this study) do not meet the requirements of an ASAT scenario, the choice can be made to try to upgrade the weapon's sensor instead of the SSN sensor itself. Depending on which upgrade is the most economical, a decision can be made.

Experimentation with the proposed model of this study would allow analysis of SSN sensor improvements to aid in the cost/benefit study, but it must be remembered that these evaluations are of a stochastic nature. A deterministic evaluation (if it were possible) would give more exact answers. A stochastic evaluation will only give a certain amount of confidence that a value is within a particular range.

Variance-Reduction Techniques. Another way to improve the efficiency of a simulation is through variance-reduction techniques (VRT). The precision of responses is measured by the confidence-interval width as previously analyzed (see Equation 5). These confidence intervals were dependent on the unknown sample variances (see Equation 3). If the variance could be reduced without changing the expectation, smaller confidence intervals could be obtained for the same amount of simulation (19: 612-613).

The VRT called common random numbers (CRN) is the most useful and popular VRT. The technique involves using the same stream of random numbers to drive the experiment. By doing this, alternative upgrades can be compared under similar experimental conditions. Thereby, there is more confidence that observed performance differences are due to system configurations rather than to fluctuations of the experimental conditions (the random number generator) (19:613).

The following explanation will show how CRN can reduce the variance (19:614). Consider two upgrades that are run through the model and produce cross-track errors of C_{1j} and C_{2j}, respectively. We can estimate the value of the difference, Z_j, between the two systems as shown previously leading to Equation 8. If the simulations of the two upgrades are done independently (i.e., different random number seeds), C_{1j} and C_{2j} will be independent and $Cov(C_{1j},C_{2j}) = 0$. By using the same stream of random numbers, C_{1j} and C_{2j} will be positively correlated (19:614). Therefore, $Cov(C_{1j},C_{2j}) > 0$ and the variance will be reduced as shown by (19:614):

$$Var[\overline{Z}(n)] = \frac{Var(Z_j)}{n} \tag{9}$$

$$= \frac{Var(C_{1j}) + Var(C_{2j}) - 2\,Cov(C_{1j},C_{2j})}{n}$$

This VRT could easily be implemented in the model of this study by using the same stream of seed numbers (SLAM II has this capability) for each experiment within the observation generation code.

Refraction Considerations

To better model the truth orbit from Step 1 of the Methodology section, atmospheric effects on propagation of radio waves should be considered. The atmosphere introduces an error in the direction of a satellite from a sensor. This direction error results from the refraction of the radio waves by the earth's atmosphere. Refraction is simply the bending of the electromagnetic waves (both visible and radio waves among these) as they propagate through the atmosphere according to iterations of Snell's Law

$$\begin{aligned} n(0)\sin(i) &= n(1)\sin(r) \\ n(1)\sin(r) &= n(2)\sin(r2) \\ n(2)\sin(r2) &= n(3)\sin(r3) \\ &\vdots \end{aligned} \tag{10}$$

across layers of materials having index of refraction values n(0), n(1), n(2), and n(3), and angles of incidence (i,r,r2,...) on the left side of the equations and angles of refraction (r,r2,r3,...) on the right side of the equations. The atmosphere can be considered as several thin layers with differing indexes of refraction (9:77-79). Refraction within a two-dimensional plane is assumed, therefore the satellites azimuth would remain constant. This assumption can be visualized by thinking of a two-dimensional plane that passes through the sensor and the satellite with all refraction occurring along this plane. Thereby, the azimuth angle would not change since the refraction is along this plane.

Because of the effect of refraction as described above, the radio wave is physically displaced and the satellite's apparent elevation, as measured by a sensor, is larger than the satellite's true elevation. It is assumed that the refraction errors in the satellite's observed range are orders of magnitude less then the errors in the satellite's elevation and are considered negligible.

Since Snell's Law applies to both radio and visible light waves, values of refraction for visible light waves can closely represent those of radio waves (an insignificant error is introduced because of the differences in wavelengths of radio and visible light waves) (27). From the 1991 Astronomical Almanac, a formula for refraction for elevations greater than 15 degrees is (6:B62):

$$R = \frac{0.00452\,P}{(273+T)\tan a} \tag{11}$$

where R is the refraction in degrees, P is the barometric pressure in millibars, T is the temperature in degrees Celsius, and a is the apparent elevation in degrees. Equation 11 is usually accurate to about 0.0017 degrees for elevations above 15 degrees. But, for altitudes below 15 degrees, the error increases rapidly and the approximate formula

$$R = \frac{P(0.1594 + 0.0196a + 0.00002a^2)}{(273 + T)(1 + 0.505a + 0.0845a^2)} \tag{12}$$

is used instead. Using Equations 11 and 12, the relationship between the satellite's apparent elevation and the amount of refraction error is shown in Figure 3 below. These values are dependent on temperature and pressure differences in the atmosphere. The values shown in Figure 3 are for average atmospheric conditions (P = 1013.3 millibars and T = 10 degrees Celsius). Elevations of less than 1.9 degrees were not computed because the elevation limits of sensors included in this study did not go below 1.9 degrees.

By comparing the refraction errors in Figure 3 to the sensor elevation sigma errors in Table 1, the significance of refraction errors can be addressed. A strict comparison cannot be made because each sensor's elevation sigma errors are an average of the sigma errors from the minimum to the maximum elevation of the sensor. At low elevations, the elevation sigma errors are the highest and the errors decrease as the elevation angle increases to the sensor limit. Therefore, by stating that a sensor's elevation sigma is 0.0230 degrees (Eglin's from Table 1) does not mean that this is the sensor's error at 10 degrees or at 80 degrees but only an average within the limits of the sensor. At very low elevations, the refraction error is an order of magnitude

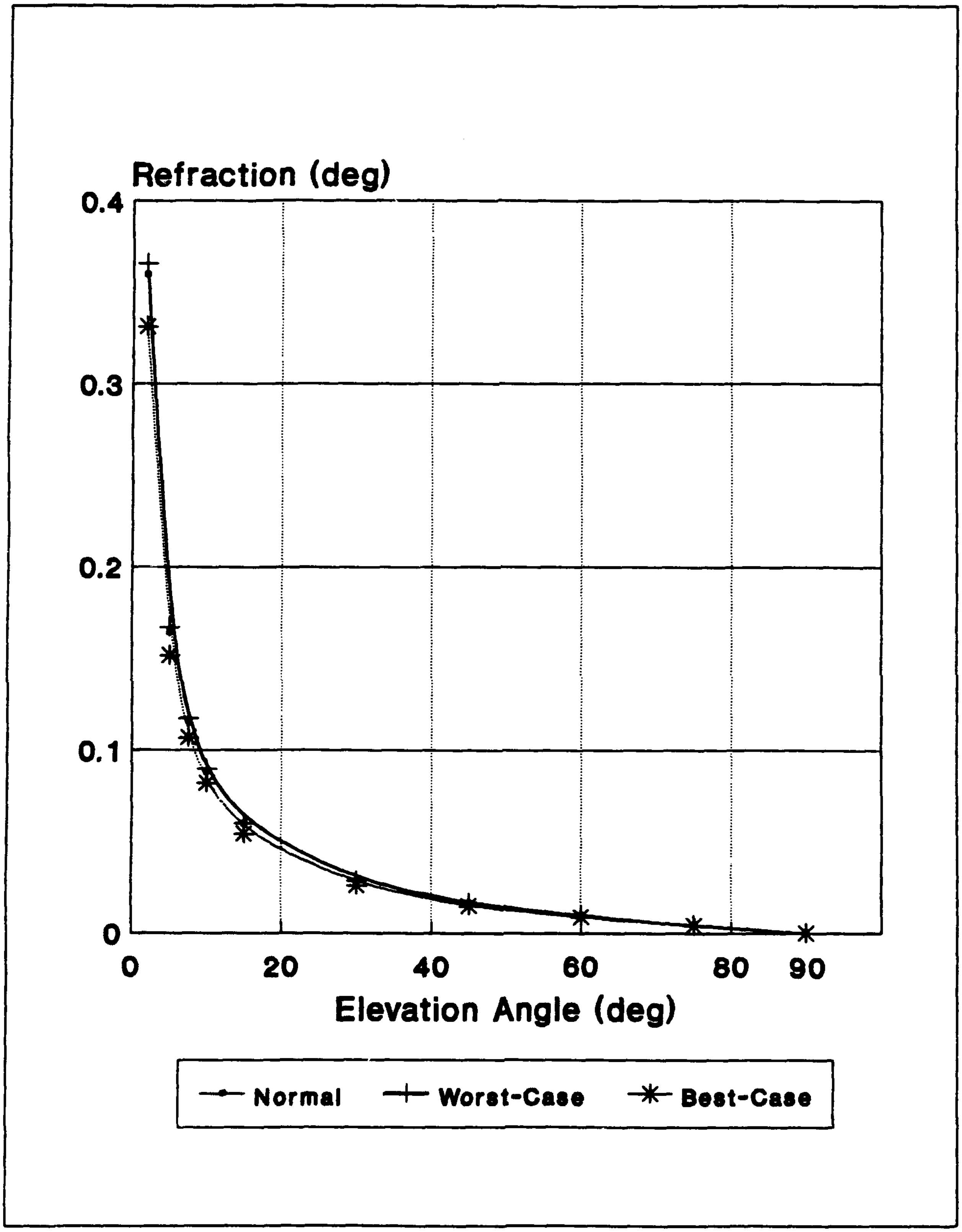

Figure 3. Refraction Effects of the Atmosphere on Elevation Angle Error With Varying Atmospheric Conditions

larger than the sensor elevation sigma errors -- as might be expected, because of the averaging of sensor sigmas. At low elevations (about 10 to 50 degrees) the refraction error is on the same order as the sensor error. And at high elevations (about 60 to 90 degrees) the refraction error is an order of magnitude less than the sensor error. Even considering the averaging of sensor sigmas, it is clear that refraction error is not an insignificant effect at very low and low elevations.

To get an idea of the magnitude of the errors resulting from refraction a simple scenario can be considered (also, see Figure 4): A sensor at sea-level views a satellite at an altitude of 600 km at an apparent elevation of 10 degrees. The refraction error would be about 0.0883 degrees which, applying simple geometry, would correspond to an error distance of 925 meters. At an apparent elevation of 75 degrees, the refraction error would be about 0.0043 degrees which corresponds to an error distance of only 45 meters.

Relative maximum and minimum values for refraction, under other than normal atmospheric conditions, can be found to determine worst and best-case scenarios for refraction effects. The value for refraction is proportional to the pressure divided by the temperature. Therefore, atmospheric conditions for a worst-case scenario would be low temperatures with high pressures and conditions for a best-case scenario would be high temperatures and low pressure.

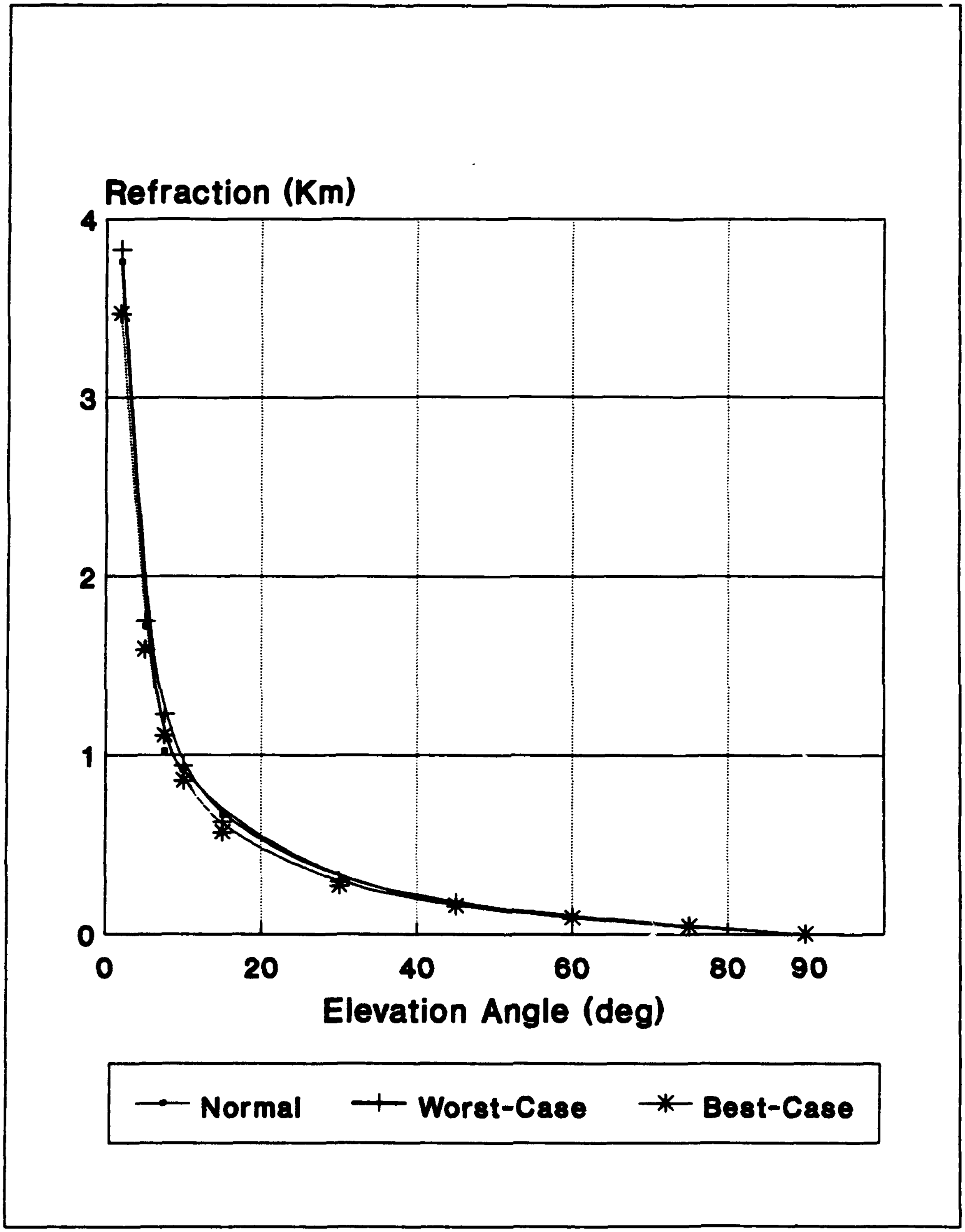

Figure 4. Refraction Effects of the Atmosphere on Elevation Distance Error Viewing a Satellite at 600 km

Consider the radar at Eglin as an example of a best and worst-case scenario. For data going back 30 years, the average monthly maximum and minimum temperatures were 32 and 6 degrees Celsius and the pressure was 1010.9 and 1016.7 millibars, respectively. Using these extremes, a worst-case scenario would be where T = 6 degrees Celsius and P = 1016.7 millibars and a best-case scenario would be where T = 32 degrees Celsius and P = 1010.9 millibars. Figure 3 shows curves (using Equations 11 and 12) for the refraction error under these worst and best-case scenarios.

Figures 3 and 4 show that the refraction errors between best and worst-case scenarios are only somewhat significant at very low elevations. For example, for a satellite at an altitude of 600 km and an apparent elevation of 1.9 degrees the difference between best and worst-case scenarios of 0.0360 degrees corresponds, from simple geometry, to an elevation distance error of 358 meters. At an apparent altitude of 30 degrees the difference is 0.0026 degrees which corresponds to an elevation distance error of only 27 meters.

Refraction errors (based on standard atmospheric conditions) could be incorporated into the truth observations of the model, as mentioned above, by correcting the computed truth elevation for the refraction error at the elevation angle the observation was taken.

Two sensors of the SSN -- Eglin and Pirinclik (the latter of which was not considered in this study) have the capability to provide near real-time atmospheric data for refraction correction with a newer system called the Improved Radar Calibration System (IRCS) (Note: the sigmas and biases used in this study are from 1987 and it is not known if they were calculated with or without the new IRCS system at Eglin operational) (11:3-6).

The other radars considered in this study do not have this capability and could potentially improve their observational data if they upgraded with the IRCS. It may be possible that the these sensors correct for refraction (based on normal atmospheric conditions) but cannot correct on a real-time basis with changing atmospheric conditions. In order to determine if refraction corrections improve the accuracy of orbit predictions, this possible upgrade to IRCS could be incorporated in the model presented in this study by correcting the representative elevation observational data for refraction with Equations 11 and 12 within the SLAM II/FORTRAN observation generation code. In order to do this, though, real-time atmospheric conditions would have to be known for the period of time the model was being run. If the sensors do correct for refraction under normal atmospheric conditions, the IRCS upgrade could be modeled by subtracting off refraction effects under normal atmospheric conditions from the real-time conditions and adding the difference to the elevation observation data.

Differential Correction Process

Without the differential correction software actually used by the SSC, a differential correction code should be written with several considerations in mind. A more detailed explanation of the differential correction process along with major considerations follows.

As discussed in the literature review, a differential correction is used to improve the accuracy of a preliminary orbit determination. In an ASAT scenario, at the time of handoff to a nearby ASAT facility, this preliminary orbit will be better defined (differential corrections have been made accounting for general perturbative effects) than as presented in the literature review where only two-body effects were accounted for in the preliminary determination. Therefore, the differential correction process will start with a good description of the ellipse and will not be hindered by a single sensor track. It may be possible that a differential correction made with a less accurate sensor could degrade the accuracy of the preliminary determination. This could be analyzed in the model by comparing the single sensor updated orbit prediction and the preliminary orbit prediction to the truth orbit prediction. Then, by varying the sigmas of the sensor, it could be determined what level of improvement the sensor would need to aid in the final orbit prediction.

The differential correction process is illustrated in Figure 5. The following discussion of this process will be

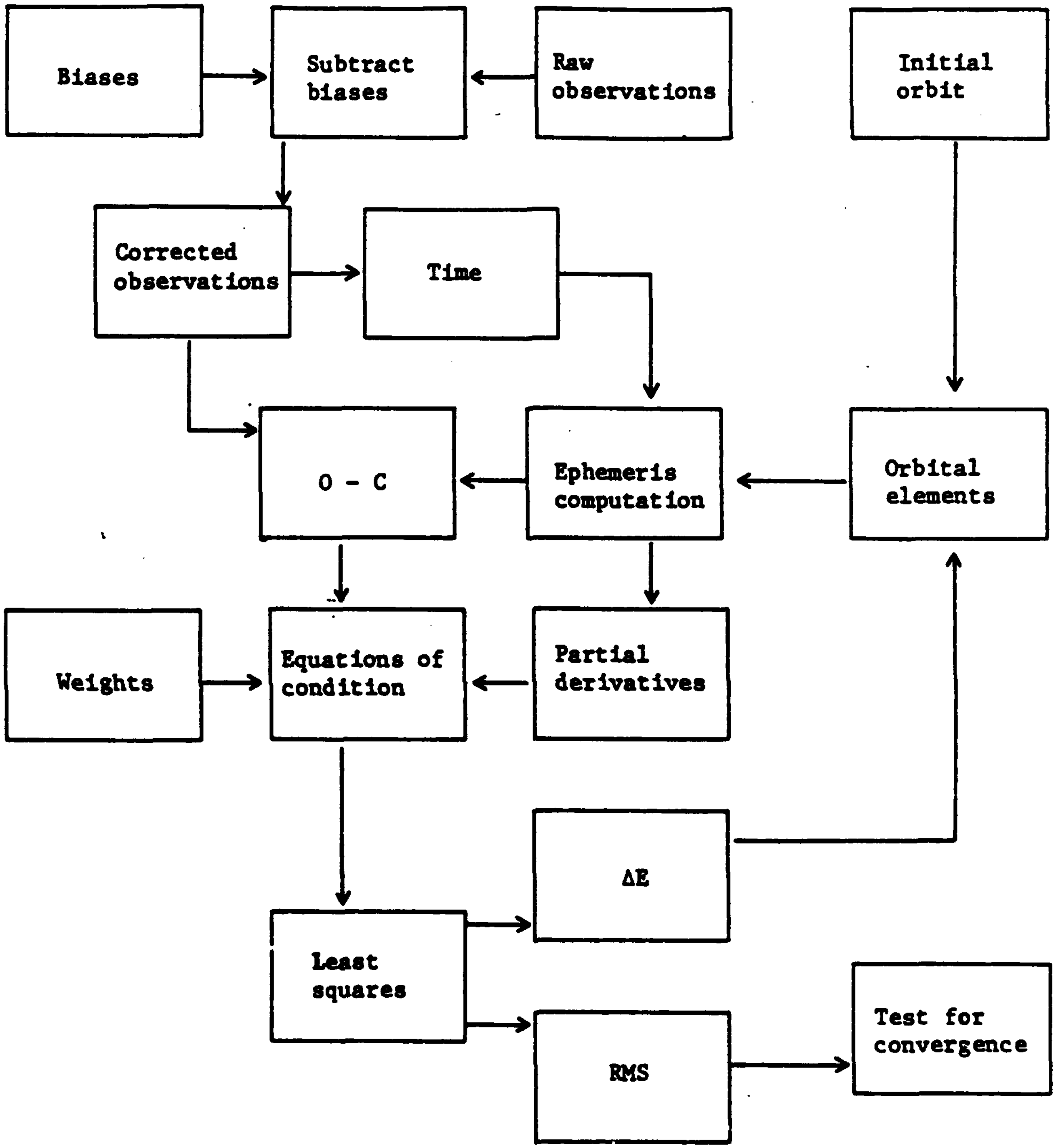

Figure 5. Differential Correction Process (Reprinted from 11:2-9)

tailored to an ASAT scenario.

The biases from the observational data from the single sensor track are subtracted out (the biases are updated weekly at the SSC) and are termed the corrected observations. Ephemeris points are calculated, using the preliminary orbit prediction, at the corresponding times of the corrected observations (23:161).

The rest of the process is largely based on the concept of residuals. Residuals are the difference in observations of the computed elements from the preliminary prediction and the actual corrected observations (O-C in Figure 5). These residuals are then set equal to the sum of the six partial derivatives of the observed parameter (e.g., elevation or range) with respect to the unknown improvement of each orbital element (the equations of condition in Figure 3) (3:123-124).

The partial derivatives are nearly impossible to obtain analytically, therefore they are obtained numerically by changing the orbital elements one at a time by a small and known amount (usually 1 or 2 percent of the original elements) and recomputing the ephemeris (23:163; 3:124).

After solving for the partial derivatives, the equations of condition have one set of unknowns -- the amount of change in the original orbital elements. This amount of change is solved for by the method of batch least squares which simply finds the curve that causes the sum of the square of the residuals to be a minimum (called the RMS -- root mean square) (3:125).

From this point, the solved changes in the elements are added back into the original orbital elements to produce a corrected element set and the process starts over again with the computation of new residuals. This iterative process requires a convergence criteria. Convergence occurs when the difference in the RMS between two iterations is less than a specified value (the SSC uses values ranging from 0.001 to 1.0 km) (3:125).

The added weights as seen in Figure 5 would need not be considered for a single sensor scenario. These weights are used to weight observations from different sensors (i.e., more accurate sensors would have their observations weighted more than a less accurate sensor).

V. Conclusions and Recommendations

Conclusions

This study's main premise is that a simulation model based on stochastic processes is a viable alternative to the ineffective, classical approach of using historical data for assessing orbit prediction accuracies of the SSC relative to the U.S ASAT mission. The basic stochastic process of the preliminary model was developed; mainly, the random observations for input into a differential correction process to produce statistically precise responses. A simulation to model the SSC orbit prediction process may have been too computer intensive for efficient use 13 years ago; but, through up-to-date statistical analysis (and the aid of present-day computer resources), it has been shown that it is feasible to configure this model to run efficiently and effectively and the prospect of simulation should be reconsidered. The proposed configuration will limit each experiment to the minimum required runs while still retaining precision; utilize experimental design to limit the amount of simulation required; and, employ variance-reduction techniques to obtain better precision or again reduce the amount of simulation required.

The follow-on model, for which the framework has been provided in this study, will closely imitate the real world of ephemeris computations generated by the SSC with perturbation and differential correction processes. The major limitations of this study are reflected in recommendations for further study to follow.

Recommendations For Further Study

Differential correction code similar to or actually used by the SSC would be instrumental in further developing the model proposed in this study. Requests for the code were turned downed by AFSPACECOM based on questionable technical and security concerns, and a need-to-know basis. Further requests of the code from AFSPACECOM backed by this study may yield different results.

Upon implementation of this model with a differential correction code, a major area of concern that should be addressed in today's tightly-budgeted environment is a cost/benefit analysis of sensor upgrades (briefly discussed in Chapter IV). The research should focus on the various missions of the SSN and determine if orbit prediction accuracies improvements are warranted. If warranted, alternatives to sensor upgrade should be researched and a detailed cost/benefit analysis performed.

Lastly, to determine the utility of sensor upgrades to all missions of the SSC, the model needs to be expanded to account for multiple satellite passes over multiple sensors.

Appendix A: SLAM II/FORTRAN Observation Generation Code

```
GEN,OBRIEN,SSN,10/11/91,1;
LIM,,2,100;
NETWORK;
      CREATE;
      EVENT,1,1;
      TERM;
      ENDNETWORK;
INIT;
FIN;


      PROGRAM MAIN
      DIMENSION NSET(10000)
      INCLUDE 'SLAM$DIR:PARAM.INC'
      COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW, II, MFA,
     1MSTOP,NCLNR, NCRDR, NPRNT, NNRUN, NNSET, NTAPE, SS(MEQT),
     2SSL(MEQT),TNEXT, TNOW, XX(MMXXV)
      COMMON QSET(10000)
      EQUIVALENCE (NSET(1),QSET(1))
      NNSET=10000
      NCRDR=5
      NPRNT=6
      NTAPE=7
      NPLOT=2
      CALL SLAM
      STOP
      END
C
      SUBROUTINE EVENT(I)
      INCLUDE 'SLAM$DIR:PARAM.INC'
      COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW, II, MFA,
     1MSTOP,NCLNR, NCRDR, NPRNT, NNRUN, NNSET, NTAPE, SS(MEQT),
     2SSL(MEQT),TNEXT, TNOW, XX(MMXXV)

*************************************************************************
*    SENSOR NUMBER              CORRESPONDING SENSOR NUMBER            *
*    -------------              ---------------------------            *
*    342 FLYINGDALES            1                                      *
*    386 OTIS                   2                                      *
*    393 SHEMYA                 3                                      *
*    396 CAVALIER               4                                      *
*    399 EGLIN                  5                                      *
*************************************************************************
* TERMINOLOGY:                                                          *
*      NOTRACKS    :  TOTAL NO. OF TRACKS FROM THE DIFFERENT SENSOR/    *
*                     SATELLITE COMBINATIONS                            *
*      MAXNOBS     :  THE NO. OF OBSERVATIONS FOR THE SENSOR/SATELLITE  *
*                     COMBINATION WITH THE MOST OBSERVATIONS            *
*      NOBS(K)     :  NUMBER OF OBSERVATIONS FOR EACH TRACK            *
```

```
*       SENSOR(K)   :  SENSOR NUMBER AS DEFINED ABOVE FOR EACH TRACK        *
*       SENSAT(K)   :  THE SENSOR/SATELLITE COMBINATION FOR EACH TRACK      *
*       AZSIGM(I)   :  SENSOR(I) AZIMUTH NOISE SIGMA                        *
*       ELSIGM(I)   :    "       ELEVATION  "     "                         *
*       RSIGM(I)    :    "       RANGE      "     "                         *
*       RRSIGM(I)   :    "       RANGE-RATE "     "                         *
*       ELBIAS(I)   :    "       AZIMUTH  BIAS                              *
*       AZBIAS(I)   :    "       ELEVATION  "                               *
*       RBIAS(I)    :    "       RANGE      "                               *
*       RRBIAS(I)   :    "       RANGE-RATE "                               *
*       DATE(J)     :  DATE OF JTH OBSERVATION                              *
*       TIME(J)     :  TIME OF JTH OBSERVATION                              *
*       AZ(J)       :  AZIMUTH   OF JTH OBSERVATION                         *
*       EL(J)       :  ELEVATION  "  "      "                               *
*       R(J)        :  RANGE      "  "      "                               *
*       RR(J)       :  RANGE-RATE "  "      "                               *
*       SIGMA.DAT   :  FILE OF THE SENSORS' NOISE SIGMAS                    *
*       BIAS.DAT    :   "    "   "     "        BIASES                      *
*     SSSOOOOO.TRU :  THE INPUT OBSERVATIONS FOR EACH SENSOR/SATELLITE     *
*                     COMBINATION                                          *
*     SSSOOOOO.OUT :  THE OUTPUT OBSERVATIONS FOR EACH SENSOR/SATELLITE    *
*                     COMBINATION (ADJUSTED WITH SIGMAS AND BIASES)        *
*************************************************************************

      INTEGER  MAXNOBS, NOTRACKS, I, J, K

      PARAMETER(MAXNOBS=1080)
      PARAMETER(NOTRACKS=30)

      CHARACTER*7 DATE(1:MAXNOBS)
      CHARACTER*8 TIME(1:MAXNOBS)

      INTEGER NOBS(1:NOTRACKS), SENSOR(1:NOTRACKS)
      CHARACTER*12 SENSAT(1:NOTRACKS), SENSATOUT(1:NOTRACKS)

      REAL AZ(1:MAXNOBS), EL(1:MAXNOBS), R(1:MAXNOBS), RR(1:MAXNOBS)

      REAL AZSIGM(1:5), ELSIGM(1:5), RSIGM(1:5), RRSIGM(1:5)
      REAL AZBIAS(1:5), ELBIAS(1:5), RBIAS(1:5), RRBIAS(1:5)

      OPEN(UNIT=14,FILE='PARAM.DAT',STATUS='OLD')
      OPEN(UNIT=10,FILE='SIGMA.DAT',STATUS='OLD')
      OPEN(UNIT=15,FILE='BIAS.DAT',STATUS='OLD')

*************************************************************************
*  READ IN THE TRACK PARAMETERS FROM THE PARAM.DAT FILE                 *
*************************************************************************

      DO 10 I=1, NOTRACKS
          READ(14,75,END=12) NOBS(I),SENSOR(I),SENSAT(I),SENSATOUT(I)
75    FORMAT(1X,I4,2X,I1,2X,A12,2X,A12)
10    CONTINUE
12    CLOSE(14, STATUS='KEEP')
```

```
************************************************************************
*  READ THE SIGMA DATA FROM THE SIGMA.DAT FILE                          *
************************************************************************

      DO 15 I=1,5
        READ(10,100,END=18) AZSIGM(I), ELSIGM(I), RSIGM(I), RRSIGM(I)
100   FORMAT(1X,F13.3,2X,F13.3,2X,F13.3,2X,F13.4)
15    CONTINUE
18    CLOSE(10, STATUS='KEEP')

************************************************************************
*  READ THE BIAS DATA FROM THE BIAS.DAT FILE                            *
************************************************************************

      DO 17 I=1,5
         READ(15,200,END=19) AZBIAS(I), ELBIAS(I), RBIAS(I), RRBIAS(I)
200   FORMAT(1X,F13.3,2X,F13.3,2X,F13.3,2X,F13.4)
17    CONTINUE
19    CLOSE(15, STATUS='KEEP')


      DO 60 K=1,NOTRACKS

************************************************************************
*  READ THE OBSERVATIONS FROM THE K SSSOOOOO.TRU FILES                  *
************************************************************************

      OPEN(UNIT=25,FILE=SENSAT(K), STATUS='OLD')

      DO 20 J=1,NOBS(K)
         READ(25,300,END=25) DATE(J), TIME(J), AZ(J), EL(J), R(J),
     +        RR(J)
300   FORMAT(2X,A7,2X,A8,F9.3,F9.3,F11.3,F9.4)
20    CONTINUE
25    CLOSE(25, STATUS='KEEP')

************************************************************************
*  DISTORT THE OBSERVATIONS WITH THE SIGMAS AND BIASES                  *
*  THE 4 WITHIN RNORM IS A SEED NUMBER                                  *
************************************************************************

      DO 40 J=1,NOBS(K)
         AZ(J)=AZ(J) + RNORM(ELBIAS(SENSOR(K)),ELSIGM(SENSOR(K)),4)
         EL(J)=EL(J) + RNORM(AZBIAS(SENSOR(K)),AZSIGM(SENSOR(K)),4)
         R(J)=R(J) + RNORM(RBIAS(SENSOR(K)),RSIGM(SENSOR(K)),4)
         RR(J)=RR(J) + RNORM(RRBIAS(SENSOR(K)),RRSIGM(SENSOR(K)),4)
         40    CONTINUE

************************************************************************
*  WRITE THE DISTORTED OBSERVATIONS TO THE K SSSOOOOO.OUT FILES
************************************************************************
```

```
      OPEN(UNIT=30, FILE=SENSATOUT(K), STATUS='NEW')

      WRITE(30,350) SENSATOUT(K)
350   FORMAT(1X,'-- ',A12,' --')

      DO 50 J=1,NOBS(K)
         WRITE(30,400) DATE(J), TIME(J), AZ(J), EL(J), R(J), RR(J)
400   FORMAT(3X,A7,2X,A8,F9.3,F9.3,F11.3,F9.4)
50    CONTINUE
      CLOSE(30, STATUS='KEEP')

60    CONTINUE

      RETURN
      END
```

Appendix B: Input Data Files for Observation Generation Code

-- BIAS.DAT --

-.017	-.030	-1.147	.0031
-.008	-.013	.008	.0002
-.014	-.008	.005	-.0002
-.004	-.015	.016	.0007
-.013	-.016	-.029	.0000

-- SIGMA.DAT --

.042	.031	2.718	.0022
.039	.034	.037	.0025
.028	.017	.016	.0018
.009	.010	.045	.0010
.019	.023	.021	.0000

-- PARAM.DAT --

28	1	34216609.TRU	34216609.OUT
34	1	34220465.TRU	34220465.OUT
34	1	34220510.TRU	34220510.OUT
45	1	34220804.TRU	34220804.OUT
23	1	34220985.TRU	34220985.OUT
31	1	34221014.TRU	34221014.OUT
316	2	38616609.TRU	38616609.OUT
695	2	38620465.TRU	38620465.OUT
710	2	38620510.TRU	38620510.OUT
922	2	38620804.TRU	38620804.OUT
267	2	38620985.TRU	38620985.OUT
759	2	38621014.TRU	38621014.OUT
633	3	39316609.TRU	39316609.OUT
808	3	39320465.TRU	39320465.OUT
806	3	39320510.TRU	39320510.OUT
1080	3	39320804.TRU	39320804.OUT
650	3	39320985.TRU	39320985.OUT
935	3	39321014.TRU	39321014.OUT
67	4	39616609.TRU	39616609.OUT
160	4	39620465.TRU	39620465.OUT
163	4	39620510.TRU	39620510.OUT
249	4	39620804.TRU	39620804.OUT
148	4	39620985.TRU	39620985.OUT
191	4	39621014.TRU	39621014.OUT
290	5	39916609.TRU	39916609.OUT
311	5	39920465.TRU	39920465.OUT
276	5	39920510.TRU	39920510.OUT
477	5	39920804.TRU	39920804.OUT
284	5	39920985.TRU	39920985.OUT
348	5	39921014.TRU	39921014.OUT

Appendix C: Sample SSS00000.TRU and SSS00000.OUT Files

Date	Time	Az(deg)	El(deg)	R(km)	RR(km/sec)
-- 39620985.TRU --					
01Nov91	10:59:09	325.483	87.697	423.681	0.1032
01Nov91	10:59:11	358.949	86.515	424.127	0.3488
01Nov91	10:59:13	13.058	84.800	425.064	0.5932
01Nov91	10:59:15	19.948	82.940	426.487	0.8355
01Nov91	10:59:17	23.920	81.036	428.392	1.0750
01Nov91	10:59:19	26.483	79.123	430.772	1.3109
01Nov91	10:59:21	28.268	77.218	433.620	1.5425
01Nov91	10:59:23	29.580	75.330	436.926	1.7693
01Nov91	10:59:25	30.586	73.465	440.680	1.9906
01Nov91	10:59:27	31.381	71.629	444.871	2.2060
01Nov91	10:59:29	32.025	69.825	449.487	2.4151
01Nov91	10:59:31	32.558	68.057	454.513	2.6175
01Nov91	10:59:33	33.006	66.325	459.938	2.8131
01Nov91	10:59:35	33.389	64.633	465.747	3.0016
01Nov91	10:59:37	33.720	62.982	471.926	3.1830
01Nov91	10:59:39	34.008	61.372	478.460	3.3571
01Nov91	10:59:41	34.262	59.804	485.335	3.5241
01Nov91	10:59:43	34.488	58.279	492.537	3.6839
01Nov91	10:59:45	34.690	56.797	500.051	3.8367
01Nov91	10:59:47	34.872	55.357	507.864	3.9826
01Nov91	10:59:49	35.036	53.960	515.963	4.1218
01Nov91	10:59:51	35.186	52.604	524.332	4.2545
01Nov91	10:59:53	35.323	51.289	532.961	4.3808
01Nov91	10:59:55	35.449	50.015	541.837	4.5011
01Nov91	10:59:57	35.565	48.780	550.947	4.6154
01Nov91	10:59:59	35.673	47.583	560.280	4.7242
01Nov91	11:00:01	35.773	46.425	569.825	4.8276
01Nov91	11:00:03	35.866	45.302	579.571	4.9258
01Nov91	11:00:05	35.953	44.215	589.509	5.0191
01Nov91	11:00:07	36.034	43.162	599.629	5.1077
01Nov91	11:00:09	36.111	42.142	609.922	5.1919
01Nov91	11:00:11	36.183	41.154	620.379	5.2719
01Nov91	11:00:13	36.251	40.197	630.992	5.3479
01Nov91	11:00:15	36.315	39.270	641.753	5.4201
01Nov91	11:00:17	36.377	38.371	652.655	5.4887
01Nov91	11:00:19	36.435	37.500	663.690	5.5539
01Nov91	11:00:21	36.490	36.656	674.853	5.6159
01Nov91	11:00:23	36.542	35.837	686.136	5.6748
01Nov91	11:00:25	36.592	35.043	697.535	5.7309
01Nov91	11:00:27	36.640	34.272	709.042	5.7842
01Nov91	11:00:29	36.686	33.524	720.654	5.8350
01Nov91	11:00:31	36.730	32.798	732.365	5.8833
01Nov91	11:00:33	36.773	32.093	744.171	5.9293
01Nov91	11:00:35	36.813	31.408	756.066	5.9731

01Nov91	11:00:37	36.852	30.742	768.046	6.0149
01Nov91	11:00:39	36.890	30.095	780.109	6.0548
01Nov91	11:00:41	36.927	29.465	792.249	6.0928
01Nov91	11:00:43	36.962	28.853	804.463	6.1290
01Nov91	11:00:45	36.996	28.258	816.748	6.1636
01Nov91	11:00:47	37.029	27.678	829.101	6.1966
01Nov91	11:00:49	37.060	27.113	841.518	6.2282
01Nov91	11:00:51	37.091	26.563	853.997	6.2584
01Nov91	11:00:53	37.121	26.027	866.535	6.2872
01Nov91	11:00:55	37.150	25.505	879.129	6.3148
01Nov91	11:00:57	37.178	24.995	891.778	6.3411
01Nov91	11:00:59	37.206	24.498	904.478	6.3664
01Nov91	11:01:01	37.233	24.013	917.227	6.3905
01Nov91	11:01:03	37.259	23.540	930.024	6.4137
01Nov91	11:01:05	37.284	23.078	942.865	6.4359
01Nov91	11:01:07	37.309	22.627	955.751	6.4571
01Nov91	11:01:09	37.333	22.186	968.678	6.4775
01Nov91	11:01:11	37.357	21.755	981.645	6.4971
01Nov91	11:01:13	37.380	21.333	994.650	6.5158
01Nov91	11:01:15	37.403	20.921	1007.692	6.5338
01Nov91	11:01:17	37.425	20.518	1020.769	6.5511
01Nov91	11:01:19	37.446	20.123	1033.880	6.5677
01Nov91	11:01:21	37.468	19.737	1047.023	6.5836
01Nov91	11:01:23	37.488	19.359	1060.198	6.5989
01Nov91	11:01:25	37.509	18.988	1073.403	6.6137
01Nov91	11:01:27	37.529	18.625	1086.637	6.6278
01Nov91	11:01:29	37.548	18.269	1099.898	6.6415
01Nov91	11:01:31	37.568	17.921	1113.187	6.6546
01Nov91	11:01:33	37.587	17.579	1126.501	6.6672
01Nov91	11:01:35	37.605	17.243	1139.839	6.6793
01Nov91	11:01:37	37.624	16.914	1153.202	6.6910
01Nov91	11:01:39	37.642	16.591	1166.587	6.7022
01Nov91	11:01:41	37.659	16.274	1179.994	6.7131
01Nov91	11:01:43	37.677	15.962	1193.423	6.7235
01Nov91	11:01:45	37.694	15.656	1206.872	6.7336
01Nov91	11:01:47	37.711	15.356	1220.341	6.7433
01Nov91	11:01:49	37.728	15.060	1233.829	6.7526
01Nov91	11:01:51	37.744	14.770	1247.336	6.7616
01Nov91	11:01:53	37.760	14.484	1260.860	6.7703
01Nov91	11:01:55	37.776	14.204	1274.401	6.7787
01Nov91	11:01:57	37.792	13.928	1287.958	6.7868
01Nov91	11:01:59	37.808	13.656	1301.532	6.7946
01Nov91	11:02:01	37.823	13.389	1315.120	6.8021
01Nov91	11:02:03	37.838	13.125	1328.724	6.8094
01Nov91	11:02:05	37.853	12.866	1342.342	6.8164
01Nov91	11:02:07	37.868	12.611	1355.973	6.8231
01Nov91	11:02:09	37.883	12.360	1369.618	6.8297
01Nov91	11:02:11	37.898	12.112	1383.276	6.8360
01Nov91	11:02:13	37.912	11.868	1396.946	6.8421
01Nov91	11:02:15	37.926	11.628	1410.628	6.8479
01Nov91	11:02:17	37.940	11.391	1424.321	6.8536
01Nov91	11:02:19	37.954	11.157	1438.026	6.8591
01Nov91	11:02:21	37.968	10.926	1451.742	6.8644

01Nov91	11:02:23	37.982	10.699	1465.467	6.8695
01Nov91	11:02:25	37.995	10.475	1479.203	6.8744
01Nov91	11:02:27	38.009	10.253	1492.949	6.8792
01Nov91	11:02:29	38.022	10.035	1506.704	6.8838
01Nov91	11:02:31	38.035	9.819	1520.468	6.8883
01Nov91	11:02:33	38.048	9.606	1534.241	6.8925
01Nov91	11:02:35	38.061	9.396	1548.022	6.8967
01Nov91	11:02:37	38.074	9.188	1561.811	6.9007
01Nov91	11:02:39	38.087	8.983	1575.608	6.9046
01Nov91	11:02:41	38.100	8.781	1589.413	6.9083
01Nov91	11:02:43	38.112	8.580	1603.225	6.9119
01Nov91	11:02:45	38.125	8.382	1617.044	6.9154
01Nov91	11:02:47	38.137	8.187	1630.870	6.9187
01Nov91	11:02:49	38.149	7.994	1644.702	6.9219
01Nov91	11:02:51	38.161	7.802	1658.541	6.9251
01Nov91	11:02:53	38.173	7.613	1672.386	6.9281
01Nov91	11:02:55	38.186	7.426	1686.237	6.9310
01Nov91	11:02:57	38.197	7.241	1700.094	6.9338
01Nov91	11:02:59	38.209	7.058	1713.956	6.9365
01Nov91	11:03:01	38.221	6.877	1727.823	6.9391
01Nov91	11:03:03	38.233	6.698	1741.696	6.9416
01Nov91	11:03:05	38.245	6.521	1755.573	6.9440
01Nov91	11:03:07	38.256	6.345	1769.455	6.9463
01Nov91	11:03:09	38.268	6.172	1783.341	6.9485
01Nov91	11:03:11	38.279	6.000	1797.232	6.9507
01Nov91	11:03:13	38.290	5.829	1811.128	6.9527
01Nov91	11:03:15	38.302	5.661	1825.027	6.9547
01Nov91	11:03:17	38.313	5.493	1838.930	6.9566
01Nov91	11:03:19	38.324	5.328	1852.837	6.9584
01Nov91	11:03:21	38.335	5.164	1866.747	6.9602
01Nov91	11:03:23	38.347	5.001	1880.661	6.9619
01Nov91	11:03:25	38.358	4.840	1894.578	6.9635
01Nov91	11:03:27	38.369	4.681	1908.498	6.9650
01Nov91	11:03:29	38.380	4.522	1922.421	6.9665
01Nov91	11:03:31	38.390	4.366	1936.347	6.9679
01Nov91	11:03:33	38.401	4.210	1950.276	6.9692
01Nov91	11:03:35	38.412	4.056	1964.207	6.9705
01Nov91	11:03:37	38.423	3.903	1978.141	6.9717
01Nov91	11:03:39	38.433	3.751	1992.078	6.9729
01Nov91	11:03:41	38.444	3.601	2006.016	6.9740
01Nov91	11:03:43	38.455	3.452	2019.957	6.9750
01Nov91	11:03:45	38.465	3.304	2033.899	6.9760
01Nov91	11:03:47	38.476	3.157	2047.844	6.9769
01Nov91	11:03:49	38.486	3.011	2061.790	6.9778
01Nov91	11:03:51	38.497	2.866	2075.739	6.9787
01Nov91	11:03:53	38.507	2.723	2089.688	6.9794
01Nov91	11:03:55	38.518	2.581	2103.640	6.9802
01Nov91	11:03:57	38.528	2.439	2117.592	6.9808
01Nov91	11:03:59	38.538	2.299	2131.546	6.9815
01Nov91	11:04:01	38.549	2.159	2145.501	6.9821
01Nov91	11:04:03	38.559	2.021	2159.458	6.9826

Date	Time	Az(deg)	El(deg)	R(km)	RR(km/sec)
-- 39620985.OUT --					
01Nov91	10:59:09	325.477	87.682	423.826	0.1029
01Nov91	10:59:11	358.924	86.513	424.167	0.3487
01Nov91	10:59:13	13.027	84.783	425.099	0.5945
01Nov91	10:59:15	19.936	82.937	426.520	0.8348
01Nov91	10:59:17	23.910	81.039	428.441	1.0755
01Nov91	10:59:19	26.467	79.117	430.723	1.3111
01Nov91	10:59:21	28.251	77.212	433.595	1.5426
01Nov91	10:59:23	29.550	75.338	437.022	1.7693
01Nov91	10:59:25	30.574	73.460	440.658	1.9923
01Nov91	10:59:27	31.367	71.618	444.819	2.2080
01Nov91	10:59:29	32.000	69.839	449.542	2.4183
01Nov91	10:59:31	32.541	68.047	454.579	2.6172
01Nov91	10:59:33	33.002	66.316	460.008	2.8138
01Nov91	10:59:35	33.381	64.630	465.826	3.0030
01Nov91	10:59:37	33.693	62.981	471.913	3.1853
01Nov91	10:59:39	33.990	61.368	478.412	3.3579
01Nov91	10:59:41	34.228	59.802	485.356	3.5258
01Nov91	10:59:43	34.475	58.260	492.607	3.6839
01Nov91	10:59:45	34.694	56.780	500.051	3.8370
01Nov91	10:59:47	34.843	55.355	507.895	3.9839
01Nov91	10:59:49	35.017	53.953	515.902	4.1235
01Nov91	10:59:51	35.171	52.582	524.372	4.2550
01Nov91	10:59:53	35.289	51.298	532.972	4.3808
01Nov91	10:59:55	35.432	50.020	541.826	4.5013
01Nov91	10:59:57	35.542	48.775	550.928	4.6165
01Nov91	10:59:59	35.646	47.597	560.314	4.7232
01Nov91	11:00:01	35.749	46.422	569.915	4.8272
01Nov91	11:00:03	35.836	45.277	579.575	4.9268
01Nov91	11:00:05	35.931	44.208	589.513	5.0176
01Nov91	11:00:07	36.021	43.176	599.690	5.1097
01Nov91	11:00:09	36.101	42.129	610.014	5.1900
01Nov91	11:00:11	36.176	41.164	620.412	5.2726
01Nov91	11:00:13	36.253	40.188	631.009	5.3491
01Nov91	11:00:15	36.295	39.264	641.802	5.4224
01Nov91	11:00:17	36.360	38.374	652.705	5.4908
01Nov91	11:00:19	36.414	37.492	663.640	5.5538
01Nov91	11:00:21	36.465	36.668	674.865	5.6155
01Nov91	11:00:23	36.530	35.828	686.149	5.6771
01Nov91	11:00:25	36.576	35.046	697.569	5.7297
01Nov91	11:00:27	36.633	34.273	709.092	5.7834
01Nov91	11:00:29	36.681	33.519	720.681	5.8357
01Nov91	11:00:31	36.736	32.792	732.340	5.8847
01Nov91	11:00:33	36.780	32.084	744.227	5.9280
01Nov91	11:00:35	36.802	31.407	756.103	5.9741
01Nov91	11:00:37	36.848	30.734	768.115	6.0159
01Nov91	11:00:39	36.879	30.099	780.115	6.0542
01Nov91	11:00:41	36.892	29.465	792.268	6.0916
01Nov91	11:00:43	36.947	28.845	804.516	6.1300
01Nov91	11:00:45	36.983	28.254	816.742	6.1645

01Nov91	11:00:47	36.993	27.682	829.154	6.1991
01Nov91	11:00:49	37.039	27.117	841.503	6.2285
01Nov91	11:00:51	37.074	26.544	854.064	6.2587
01Nov91	11:00:53	37.100	26.048	866.539	6.2876
01Nov91	11:00:55	37.146	25.508	879.116	6.3139
01Nov91	11:00:57	37.154	24.993	891.844	6.3422
01Nov91	11:00:59	37.185	24.500	904.497	6.3674
01Nov91	11:01:01	37.209	24.013	917.267	6.3896
01Nov91	11:01:03	37.233	23.542	929.975	6.4142
01Nov91	11:01:05	37.277	23.070	942.887	6.4378
01Nov91	11:01:07	37.300	22.617	955.775	6.4577
01Nov91	11:01:09	37.295	22.174	968.608	6.4788
01Nov91	11:01:11	37.335	21.750	981.718	6.4983
01Nov91	11:01:13	37.354	21.339	994.684	6.5173
01Nov91	11:01:15	37.394	20.916	1007.655	6.5358
01Nov91	11:01:17	37.410	20.509	1020.742	6.5523
01Nov91	11:01:19	37.434	20.133	1033.893	6.5692
01Nov91	11:01:21	37.457	19.744	1047.039	6.5853
01Nov91	11:01:23	37.493	19.363	1060.178	6.5997
01Nov91	11:01:25	37.495	18.991	1073.505	6.6153
01Nov91	11:01:27	37.519	18.631	1086.652	6.6285
01Nov91	11:01:29	37.523	18.255	1099.929	6.6420
01Nov91	11:01:31	37.562	17.918	1113.176	6.6551
01Nov91	11:01:33	37.557	17.589	1126.512	6.6667
01Nov91	11:01:35	37.581	17.244	1139.924	6.6813
01Nov91	11:01:37	37.601	16.917	1153.146	6.6915
01Nov91	11:01:39	37.629	16.579	1166.685	6.7024
01Nov91	11:01:41	37.646	16.283	1179.995	6.7137
01Nov91	11:01:43	37.649	15.958	1193.365	6.7263
01Nov91	11:01:45	37.678	15.640	1206.897	6.7334
01Nov91	11:01:47	37.688	15.339	1220.323	6.7422
01Nov91	11:01:49	37.706	15.058	1233.806	6.7534
01Nov91	11:01:51	37.733	14.771	1247.415	6.7613
01Nov91	11:01:53	37.762	14.472	1260.872	6.7704
01Nov91	11:01:55	37.743	14.192	1274.386	6.7789
01Nov91	11:01:57	37.782	13.923	1287.921	6.7867
01Nov91	11:01:59	37.790	13.647	1301.574	6.7950
01Nov91	11:02:01	37.806	13.381	1315.117	6.8026
01Nov91	11:02:03	37.815	13.121	1328.785	6.8105
01Nov91	11:02:05	37.830	12.873	1342.427	6.8164
01Nov91	11:02:07	37.857	12.607	1355.972	6.8238
01Nov91	11:02:09	37.862	12.347	1369.676	6.8302
01Nov91	11:02:11	37.884	12.113	1383.307	6.8365
01Nov91	11:02:13	37.886	11.872	1396.940	6.8435
01Nov91	11:02:15	37.915	11.625	1410.628	6.8487
01Nov91	11:02:17	37.924	11.379	1424.327	6.8543
01Nov91	11:02:19	37.955	11.158	1438.002	6.8599
01Nov91	11:02:21	37.962	10.913	1451.672	6.8635
01Nov91	11:02:23	37.981	10.694	1465.485	6.8700
01Nov91	11:02:25	37.981	10.475	1479.140	6.8751
01Nov91	11:02:27	37.993	10.250	1492.945	6.8810
01Nov91	11:02:29	38.016	10.012	1506.786	6.8856
01Nov91	11:02:31	38.038	9.821	1520.488	6.8897

01Nov91	11:02:33	38.041	9.602	1534.280	6.8938
01Nov91	11:02:35	38.039	9.389	1548.003	6.8964
01Nov91	11:02:37	38.045	9.169	1561.758	6.8996
01Nov91	11:02:39	38.082	8.994	1575.678	6.9054
01Nov91	11:02:41	38.080	8.780	1589.431	6.9089
01Nov91	11:02:43	38.096	8.579	1603.191	6.9128
01Nov91	11:02:45	38.112	8.390	1617.087	6.9154
01Nov91	11:02:47	38.121	8.193	1630.873	6.9188
01Nov91	11:02:49	38.133	7.993	1644.772	6.9226
01Nov91	11:02:51	38.151	7.812	1658.549	6.9260
01Nov91	11:02:53	38.179	7.615	1672.375	6.9295
01Nov91	11:02:55	38.169	7.421	1686.231	6.9323
01Nov91	11:02:57	38.165	7.222	1700.044	6.9330
01Nov91	11:02:59	38.196	7.058	1713.950	6.9377
01Nov91	11:03:01	38.185	6.859	1727.888	6.9397
01Nov91	11:03:03	38.212	6.702	1741.686	6.9419
01Nov91	11:03:05	38.239	6.512	1755.605	6.9456
01Nov91	11:03:07	38.252	6.348	1769.501	6.9474
01Nov91	11:03:09	38.248	6.180	1783.301	6.9518
01Nov91	11:03:11	38.280	5.996	1797.217	6.9517
01Nov91	11:03:13	38.263	5.825	1811.178	6.9542
01Nov91	11:03:15	38.302	5.661	1825.097	6.9535
01Nov91	11:03:17	38.305	5.479	1838.953	6.9595
01Nov91	11:03:19	38.311	5.337	1852.872	6.9598
01Nov91	11:03:21	38.318	5.160	1866.851	6.9583
01Nov91	11:03:23	38.326	5.001	1880.683	6.9611
01Nov91	11:03:25	38.336	4.840	1894.649	6.9645
01Nov91	11:03:27	38.356	4.681	1908.490	6.9658
01Nov91	11:03:29	38.353	4.507	1922.491	6.9655
01Nov91	11:03:31	38.364	4.364	1936.346	6.9690
01Nov91	11:03:33	38.390	4.210	1950.290	6.9692
01Nov91	11:03:35	38.385	4.036	1964.271	6.9714
01Nov91	11:03:37	38.400	3.905	1978.117	6.9723
01Nov91	11:03:39	38.421	3.756	1992.055	6.9740
01Nov91	11:03:41	38.423	3.597	2006.078	6.9740
01Nov91	11:03:43	38.442	3.454	2020.030	6.9762
01Nov91	11:03:45	38.427	3.314	2033.900	6.9761
01Nov91	11:03:47	38.468	3.166	2047.838	6.9775
01Nov91	11:03:49	38.472	2.999	2061.789	6.9774
01Nov91	11:03:51	38.486	2.880	2075.867	6.9789
01Nov91	11:03:53	38.481	2.719	2089.656	6.9807
01Nov91	11:03:55	38.497	2.595	2103.719	6.9815
01Nov91	11:03:57	38.531	2.443	2117.509	6.9813
01Nov91	11:03:59	38.530	2.292	2131.592	6.9822
01Nov91	11:04:01	38.545	2.149	2145.583	6.9830
01Nov91	11:04:03	38.535	2.008	2159.526	6.9833

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